Improvement in service life of skip car by using chromium carbide overlay plate with special reference to Rourkela Steel Plant

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Mechanical Engineering

by

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Under the supervision of

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This is to certify that the work presented in this dissertation entitled “Improvement in Service Life of Skip Car by Using Chromium Carbide Overlay Plate with special reference to Rourkela Steel Plant " by "*Samarendra Pattanaik*", Roll Number *612ME902*, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of *M.Tech(Research)* in *Mechanical Engineering*. Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

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Declaration of Originality

I, *Samarendra Pattanaik*, Roll Number 6*12ME902* hereby declare that this dissertation entitled “Improvement in Service Life of Skip Car by Using Chromium Carbide Overlay Plate with special reference to Rourkela Steel Plant” represents my original work carried out as a M.Tech(Research) student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "References". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

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ABSTRACT

Wear is becoming increasingly important in industrial applications, in particular due to its environmental impact through the reduction of the service life of machinery. Extremely heavy wear takes place in construction and mining, where large amounts of rocks and soil are processed. The skip car in blast furnace of RSP is used to transfer and charge raw materials such as coke, iron ore, sinter and additives like limes stone dolomites into the furnace. This Skip Car has to withstand heavy wear caused by loading and unloading of those raw materials onto the Car body, which subjects it to impact-abrasion wear caused by impacts and scratching by the minerals. Wear-resistant steels are often used as a material for this kind of machinery since it has better durability than mild steels and thus provides longer service life. At present mild steel is used as skip car liner plates in BF stock house of RSP. Its service life is found to be around 2 months. Under such circumstances a selection of high wear resistance steel is essential for better wear resistant and higher life for the skip car. Wear-resistant steels are often used as a material for this kind of machinery since it has better durability than mild steels and thus provides longer service life. Literature reveals that there are further developments in improving the wear properties of steel by using carbide coatings on base metals. Because of its immense popularity and versatility for severe abrasion applications, carbide coated products are being used in industries. Keeping this in view, the objective of this work is to investigate the performance of chromium carbide Overlay Plate to improve the service life of skip car. Experiments have been carried out (Solid particle erosion test, three body abrasion) on the developed coatings in the laboratory conditions to assess the suitability of the material for actual operations in the steel plant. Plant trials have been carried out and the results achieved are discussed in the thesis.

Keywords: wear; skip car, blast furnace, abrasion, liner plates, and chromium carbide overlay plate

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Chapter 1

INTRODUCTION

1.1 Background

Surface modification is a generic term now applied to a large field of diverse technologies that can be gainfully harnessed to achieve increased reliability and enhanced performance of industrial components. The incessant quest for higher efficiency and productivity across the entire spectrum of manufacturing and engineering industries has ensured that most modern component are subjected to increasingly harsh environments during routine operation. Critical industrial components are therefore, prone to more rapid degradation as the part fails to withstand the rigors of aggressive operating conditions and this has been taking a heavy toll of industry's economy. In an overwhelmingly large number of cases, the accelerated deterioration of parts and their eventual failure have been traced to material damage brought about by hostile environments and also by high relative motion between mating surfaces, corrosive media, extreme temperatures and cyclic stresses. Simultaneously, research efforts focused on the development of new materials for fabrication are beginning to yield diminishing returns and it appears unlikely that any significant advances in term of components performance and durability can be made only through development of new alloys.

As a result of above, the concept of incorporating engineered surfaces capable of combating the accompanying degradation phenomena like wear, corrosion and fatigue to improve component performance, reliability and durability has gained increasing acceptance in recent years. The recognition that a vast majority of engineering components fail catastrophically in service through surface related phenomena has further fueled this approach and has led to the development of the broad interdisciplinary area of surface modifications.

Thus, a protective coating deposited to act as a barrier between the surfaces of the component and the aggressive environment that it is exposed to during operation is now globally acknowledged to an attractive means to significantly reduce/suppress damage to the actual component by acting as the first line of defense.

Typically, these coatings are aimed at modifying the surface properties of critical components to provide enhanced resistance against deterioration due to mechanism such as corrosion, oxidation and wear of failure under an excessive heat load. In recent years, considerable advances in the field of coating technology have accompanied the growing realization of the immense potential of surface engineering in the modern industrial world. Consequently, there are now available a number of methods for developing a wide variety of protective coating [1].

The increasing utility and industrial adoption of surface engineering is a consequence of the significant recent advances in the field. Very rapid strides have been made on all fronts of science viz. processing, control, modeling, application developments etc. and this has made it an invaluable tools that is now been increasingly considered to be an integral part of component design. Surface modification today is best defined as ` the design of substrate and surface together as a system to give a cost effective performance enhancement , of which neither is capable of its own‘. The development of a suitable high performance coating on a component fabricated using an appropriate high strength metal/alloy offers a promising method of meeting both the bulk and surface property requirement of virtually all imagined applications. The newer surfacing techniques, along with the traditional ones, are eminently suited to modify a wide range of engineering properties. The properties that can be modified by adopting the surface engineering approach include tribological, mechanical, thermo-mechanical, electro-chemical, optical, electrical, electronics, magnetic, acoustic and biocompatible properties.

The development of surface engineering has been dynamic largely on account of the fact that it is a discipline of science and technology that is being increasingly relied upon to meet all the key modern day technological requirements such as material savings, enhanced efficiencies, environmental friendliness etc. The overall utility of the surface engineering

approach is further augmented by the fact that modifications to the component surface can be metallurgical, mechanical, chemical or physical.

Driven by technological need and fueled by exciting possibilities, novel methods for applying coating, improvements in existing methods and new application have proliferated in recent years. Surface modification technologies have grown rapidly, both in terms of finding better solutions and in the number of technology variants available, to offer a wide range of quality and cost. The significant increase in the availability of coating process of wide ranging complexity that are capable of depositing a plethora of coatings and handling components of diverse geometry today, ensures that components of all imaginable shape and size can be coated economically. Existing surface treatment and coating processes fall under three broad categories:

1. **Overlay Coatings**: This category incorporates a very wide variety of coating processes wherein a material different from the bulk is deposited on the substrate. The coating is distinct from the substrate in the as-coated condition and there exist a clear boundary at the substrate-coating interface. The adhesion of the coating to the substrate is a major issue in this process.
2. **Diffusion Coating**: Chemical interaction of the coating-forming elements(s) with the substrate by diffusion is involved in this category. New elements are diffused into the substrate surface, usually at elevated temperatures so that the composition and properties of outer layers are changed as compared to those of the bulk.
3. **Thermal or Mechanical Modification of Surfaces**: In this case, the existing metallurgy of the component surface is changed in the near-surface region either by thermal or mechanical means, usually to increase its hardness.

1.2 Problem Definition

1.2.1 A brief description on Blast Furnace

Blast Furnace is a counter current heat & mass exchanger, in which the burden solid raw materials like Iron ore, Sinter, Coke & additives / fluxes) is charged from top of the furnace & hot blast is sent through the bottom via tuyeres. The heats transferred through the

ascending hot blast to the descending burden & oxygen from the burden to the gases. In the counter current process, the iron ore & reducing agents (Coke, Coal) are transformed to hot metal & slag formed from the gangue of the iron ore, sinter & the ash of coke. The liquid hot metal & slag do not mix and remain separated from each other with the slag floating on top of the denser iron. The liquid iron & slag are separated in the cast house during casting. The other product from the blast furnace is dust laden, blast furnace gas, which is further cleaned in the gas cleaning plant and is used as a fuel all over the plant. Blast Furnace is the heart of any integrated steel plant. Hot metal, which is the raw material for steel melting, is produced from the Blast furnace. All the four nos. of Blast furnace at Rourkela Steel plant where skip charging facility is employed has been shown in figure 1.1. A model of Blast furnace is also shown in figure 1.2.

1.2.2 Function of skip car at Blast Furnace

Skip car (Fig.1.3) is used for charging of raw materials inside the Blast furnace. To charge the raw materials into the furnace, two nos. of skip car (of 8.5 m^3 volume with howling capacity of 12T at a speed of 1.8 m/s) are available. The raw materials carried by the skip for charging in to the Furnace are as follows:

- Coke: Act as a fuel, reducing agent and burden bearing material.
- Iron ore and sinter: Iron bearing material.
- Limestone as a flux.
- Manganese ore, quartzite etc. as chemical additive of iron.

One car loaded with raw material and traveling upward on inclined rail on the way to charge the material into the furnace while other empty car getting down on a parallel inclined path approaching to the respective raw material hopper. Four no's of wheel on each car are made of cast steel. Details of the skip car parts are shown in Fig.1.3. Both the skip cars are rope driven mounted on a single winch drum with two drive gear box in parallel (Fig 1.4).While one of skip car remains in skip pit to receive raw materials from hopper (Fig 1.5a), the other one remains at the top to discharge material to furnace .The raw material which are carried by the skip car to Blast Furnace are hard coke (Fig 1.5b) and iron ore, sinter and additives like Limestone, Dolomite, Quartzite etc. (Fig 1.5c). Normally hard coke of approximately 7 Ton and mixture of iron ore and sinter of 13 Ton are charged in sequence through skip car. Both

the skip cars travel in an inclined rail as shown in Fig1.6 (a-b). It takes 55 sec of travel from feeding point to discharge point.

1.2.3 Description of the Problem

The protection plates (also called Liner Plates) used in the skip cars are normally mild steel whose service life is estimated 2-4 months (Fig 1.7). Once these protection plates are worn out due to impact/sliding (Fig 1.8(a-b)), the base plate are exposed and worn out in similar fashion. If the base plates are damaged, it will lead to replacement of another skip car. Under no circumstances base plate of skip car is kept exposed to hit the raw materials. Therefore condition of liner plates has to be in healthy shape in order to extend the service life of the car. As the replacement schedule of Skip Car is 18 months, it is expected that the protection plate used should last for the same duration.

1.2.4 Consequence of the above problem

To replace the Car, the furnace has to be made shutdown for at least 8 hours which is directly related to production loss in addition to other losses incurred to many other upstream/downstream departments. Once the furnace shutdown is taken, the Consequence leads to a loss of about Rs.1, 15, 71,000(Rupees one crore fifteen lakhs seventy one thousand only) as calculated in Table-1.1.

Basis of calculation:

- Cost of production/Ton of Hot Metal = Rs.17,540.00
- NSR of hot metal in terms of pig for 1 ton = Rs.24,700.00
- Profit Margin = Rate of Hot metal/Ton – Cost of Production = Rs.7160.00

Table 1.1 Total Losses for one breakdown of skip car

Factors	**Losses**
Production Loss Due to Furnace Downtime	8 hrs. *200T of hot metal*Rs7160 per tonne = Rs.1,14,56,000
Disturbance in Burden Movement	Intangible
Replacement Cost	1.15 lakh
Man Hour Loss	Inclusive In production loss
Total Losses for one breakdown	**Rs.1, 15, 71,000**

In addition to the above loss of nearly Rs.1.15 crores per one such stoppage. Moreover, Blast furnace functioning is affected as the continuity is lost and which takes some time to revive. Keeping this in mind, use of better wear resistant plate becomes a necessity.

1.3 Present Objective

To extend the life of protection plate at least up to the time of replacement schedule of 18 months, a selection of high wear resistant steel is a must for better wear resistant properties. **Carbide coated** plate is one of the solution for these types of problems. Because of its immense popularity and versatility for severe abrasion application, Carbide coated products are being used in various industry for wear resistance applications .Keeping this in view, the objective of the present work is to investigate the wear performance of carbide coated steel plates for skip car applications in Blast Furnace.

Figure 1. 1 Blast Furnaces at Rourkela Steel Plant

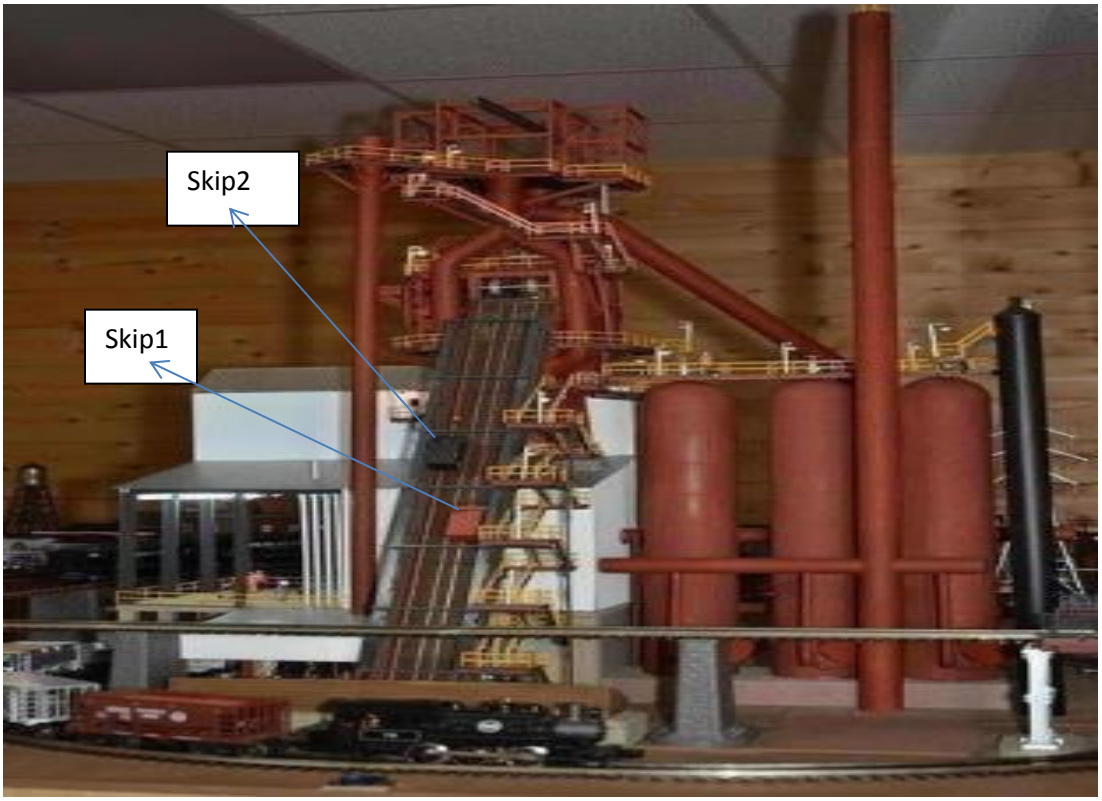
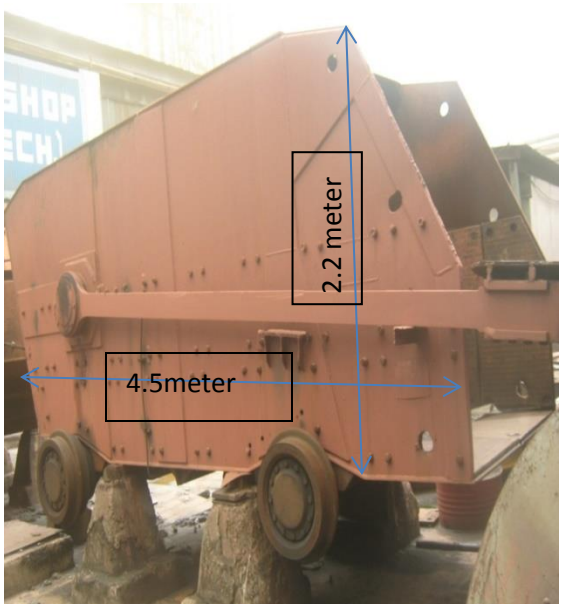


Figure 1.2 A model of Blast Furnace where both the Skips are visible

1. Skip Body
2. Skip Frame
3. Wheel Axle
4. Equliser
5. Side Liner Plate
6. Bottom Liner Plate

(a)



(b) (c)

Figure 1.3 (a, b, c) SKIP CAR body parts and outer dimensions

Figure 1.4 Drive House of Skip Car (dual gear box with rope drum**)**

Figure 1.5(a) Skip Car waiting to receive materials

Figure 1.5(b) Coke being charged to Skip Car

Figure 1.5(c) Iron Ore and Sinter being charged

Figure 1.6(a) Skip Car Inclined travel Rail

Fig 1.6(b) Twin Skip on operation

Fig 1.7 Skip Car with new mild steel liner plates replaced in-house at repair shop

(a) **(b)**

Fig1.8 (a-b) Wear Pattern of damaged Skip Car Plate

Chapter 2

Literature Survey

2.1 Objective

The purpose of this literature review is to provide background information on the issues to be considered in this thesis and to emphasize the relevance of the present study. The treatise embraces various aspects of wear and its classifications and on wear resistance coatings. This chapter includes reviews of available research reports .

On Wear mechanism and its Classification

On Wear Resistant Coatings

On Solid particle Erosion wear of materials

On Dry Sand Abrasion Wear of materials

2.2 On Wear Mechanism and its Classification

Wear is a process of removal of material from one or the other of two solid surfaces in the solid state contact, occurring when two solid surfaces are in sliding or rolling motion together according to Bhushan and Gupta [2]. The rate of removal is generally slow, but steady and continuous. Figure 2.1 shows the five main categories of wear and the specific wear mechanisms that occur in each category. Each specific mode of wear different from the next, and can be distinguished relatively easily.

Wear rate changes drastically in the range of 10^{-15} to $10^{-1}mm^3/Nm$, depending on operating conditions and material selections [3-9]. These results mean that design of operating conditions and selection of materials are the keys to controlling wear. As one way to meet these requirements, wear maps have been proposed for prediction of wear modes and

wear rates [10-11]. Wear mechanisms are described by considering complex changes during friction. In general, wear does not take place through a single wear mechanism, so understanding each wear mechanism in each mode of wear becomes important.

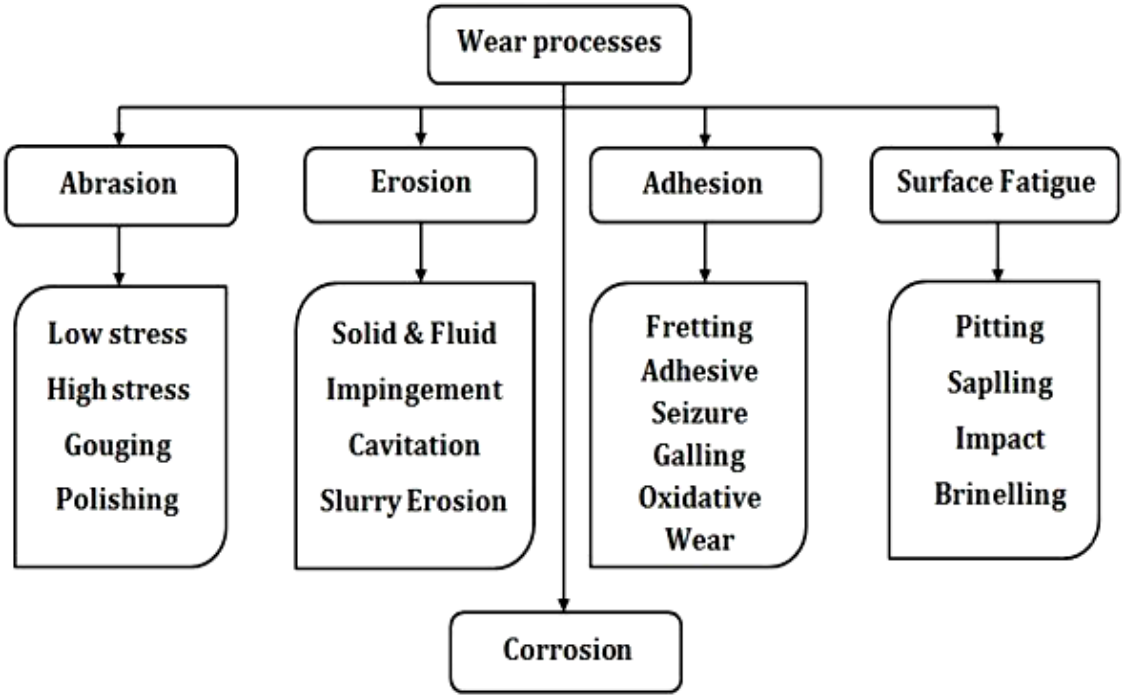


Figure 2.1 Flow chart of various wear mechanism

In order to focus on the wear mechanisms from the viewpoint of contact configurations, apparent and real contact conditions at the contact interface are introduced without particularizing about these contact configurations. Severity of contact, such as elastic contact or plastic contact, is the simplest and most direct way to think about wear mechanisms, and is a tribo-system response determined by dynamic parameters, material parameters, and atmospheric parameters. The following four wear modes are generally recognized as fundamental and major ones [12].

2.2.1 Abrasive wear

If the contact interface between two surfaces has interlocking of an inclined or curved contact, ploughing takes place in sliding. As a result of ploughing, a certain volume of

surface material is removed and an abrasive groove is formed on the weaker surface. This type of wear is called abrasive wear.

A common example of this problem is the wear of shovels on earth-moving machinery. It was originally thought that abrasive wear by grits or hard asperities closely resembled cutting by a series of machine tools or a file. It can be account for most failures in practice. Hard particles or asperities that cut or groove one of the rubbing surfaces produce abrasive wear. This hard material may be originated from one of the two rubbing surfaces. In sliding mechanisms, abrasion can arise from the existing asperities on one surface (if it is harder than the other), from the generation of wear fragments which are repeatedly deformed and hence get work hardened for oxidized until they became harder than either or both of the sliding surfaces, or from the adventitious entry of hard particles, such as dirt from outside the system. The way the grits pass over the worn surface determines the nature of abrasive wear.

The literature denotes two basic modes of abrasive wear such as two-body and three-body abrasive wear. In two-body abrasive condition; one surface is harder than the other rubbing surface. Hard asperities or rigidly held grits pass over the surface like a cutting tool is shown in figure 2.2(a). In three-body abrasive condition, generally a small particle of grit or abrasive, lodges between the two softer rubbing surfaces, abrades one or both of these surfaces is shown in figure 2.2(b). It was found that three body abrasive wear is ten times slower than two-body wear.

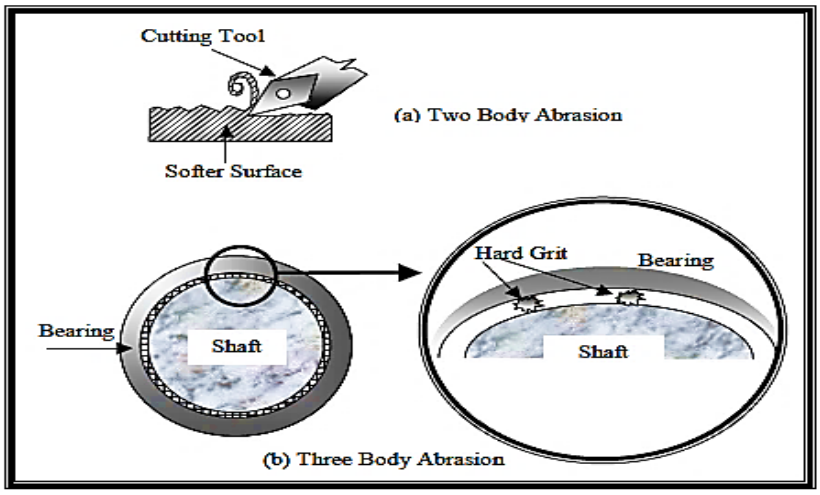


Figure 2.2 Schematic of abrasive wear phenomena [13]

2.2.2 Adhesive wear

Adhesive wear is a very serious form of wear characterized by high wear rates and a large unstable friction coefficient. It is also called galling and scuffing where interfacial adhesive junctions lock together as two surfaces slide across each other under pressure. Sliding contacts can rapidly be destroyed by adhesive wear and, in extreme cases, sliding motion may be prevented by very large coefficients of friction or seizure is shown in figure 2.3.

Most solids will adhere on contact with another solid to some extent provided certain conditions are satisfied. Adhesion between two objects casually placed together is not observed because intervening contaminant layers of oxygen, water and oil are generally present. The earth's atmosphere and terrestrial organic matter provide layers of surface contaminant on objects which suppress very effectively any adhesion between solids. Adhesion is also reduced with increasing surface roughness or hardness of the contacting bodies. Actual observation of adhesion became possible after the development of high vacuum systems which allowed surfaces free of contaminants to be prepared. Adhesion and sliding experiments performed under high vacuum showed a totally different tribological behavior of many common materials from that observed in open air.

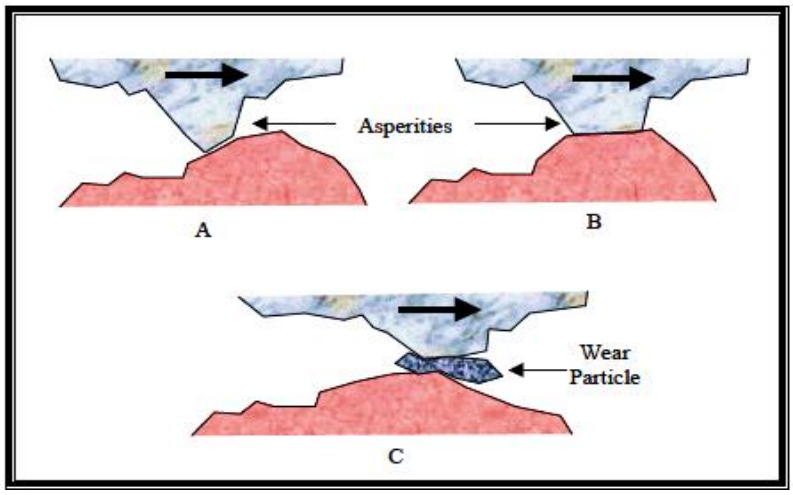


Figure 2.3 Schematic of generation of a wear particle as a result of adhesive wear process [13]

2.2.3 Erosive wear

The term 'erosive wear' refers to an unspecified number of wear mechanisms which occur when relative small particles impact against mechanical components. This definition is empirical by nature and relates more to practical considerations than to any fundamental understanding of wear.

Erosive wear is caused as a result of solid or small drops of liquid particles or gas impact against the surface of an object. The typical examples of solid particles erosive wear occurs in a wide variety of machinery and the damage to gas turbine blades when an aircraft flies through dust clouds, and the wear of pump impellers in mineral slurry processing systems. Examples include the ingestion of sand and erosion of jet engines and of helicopter blades.

Solid particle erosion is a result of the impact of a solid particle A, with the solid surface B, resulting in part of the surface B been removed is shown in figure 2.4. The solid particles or liquid drops significantly contingent on the material properties and erosion process, such as impact velocity, impact angle and particle size. Angle of impingement and movement of particle stream have significantly effect on the rate of material removal. In common superior mechanical strength of a material does not guarantee better wear resistance, hence it is required a meticulous study of material characteristics for minimization of wear. The properties of the eroding particle are also recognized as a relevant parameter in the control of this type of wear.

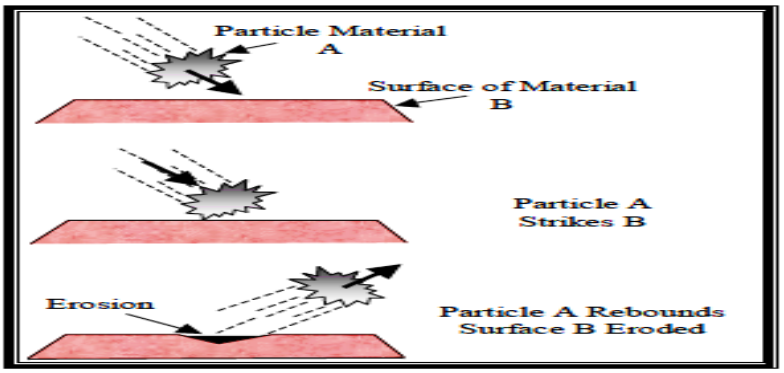


Figure 2.4 Schematic representations of the erosive wear mechanism [13]

2.2.4 Surface fatigue wear

When two surfaces slide across each other, the maximum shear stress lies some distance below the surface, causing micro cracks, which lead to failure of the component. These cracks initiate from the point where the shear stress is maximum and propagate to the surface as shown in figure 2.5.

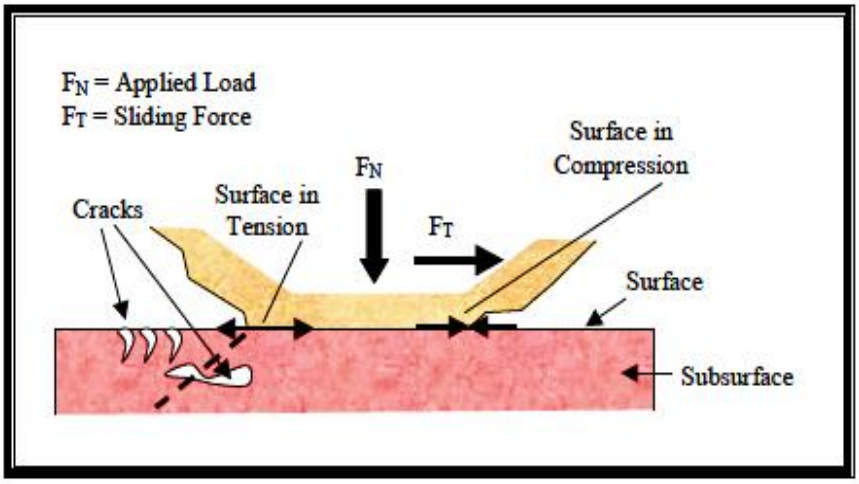


Figure 2.5 Schematic of fatigue wear, due to the formation of surface and subsurface cracks [13]

2.2.5 Corrosive wear

In corrosive wear, tribo-chemical reaction produces a reaction layer on the surface. At the same time, such layer is removed by friction is shown in figure 2.6. Therefore, relative growth rate and removal rate determine the wear rate of the reaction layers and, as a result, of the bulk material. Therefore, models of the reaction layer growth and those of the layer removal become very important.

Typical examples of corrosive wear can be found in situations when overly reactive E.P. additives are used in oil (condition sometimes dubbed as 'lubricated wear' [14] or when methanol, used as a fuel in engines, is contaminated with water and the engine experiences a rapid wear [15]. Another example of corrosive wear, extensively studied in laboratory conditions, is that of cast iron in the presence of sulphuric acid [16]. The corrosive of sulphuric acid is very sensitive to the water content and increases with acid strength until

there is less water than acid. Pure or almost pure acid is only weakly corrosive and has been used as a lubricant for chlorine compressors where oils might cause an explosion [17].

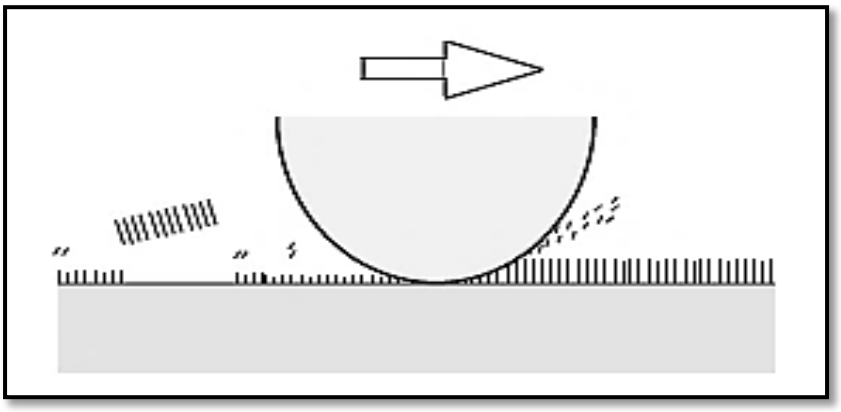


Figure 2.6 Schematic of corrosive wear, due to the formation of surface and subsurface cracks

2.3 On Wear Resistance Coating

Many industrial processes make use of plasma spayed ceramic coating, whose reproducibility is good, once the optimal set of spray parameter has been found. Although hard ceramic coatings are normally employed in wear related application, they are used in other industrial as well. For example, the food and medicine packaging industry does not only need wear resistance, but also needs the absence of heavy metal contamination: Al_2O_3 and Al_2O_3-TiO_2 are often used for this reason in that field. Therefore, plasma-sprayed hard ceramic coatings are still studied nowadays [18-20]. A through study of the wear resistance of thermally sprayed coating must involve plasma-sprayed ceramic. Much research related to the basic wear mechanisms of plasma sprayed oxides exists, science such coating have been studied for a long time [21-24]. However, there exists a few works comparing them to the characteristics of other thermally sprayed coatings as well as to other industrially widespread wear resistance coating, such as hard chrome electroplating and nickel electrode plating [25-26]. Furthermore, to fully assess the industrial applicability of thermally sprayed coating in general and of plasma sprayed oxides in particular, wear maps should be experimentally obtained, as it is currently being done for massive sintered ceramics [27-29]. Today a variety of material, e.g. carbides, oxides, metallic etc. belonging to the above category are available

commercially. The wear resistance coating can be classified into the following categories:[30]

- Carbides: WC, TiC, SiC, ZrC, Cr_2C_3 etc.
- Oxides: Al_2O_3, Cr_2O_3, TiO_2, ZrO_2 etc.
- Metallic: NiCrAlY, Triballoy etc.
- diamond

The choice of material depends on the application. However, the ceramics coating are very hard and hence on an average offer more abrasion resistance than their metallic counterparts.

2.3.1 Carbide Coatings

Amongst carbides, WC is very popular for wear and corrosion application [31]. The WC powders are clad with a cobalt layer. During spraying the cobalt layer undergoes melting and upon solidification form a metallic matrix in which the hard WC particles remains embedded. Spraying of WC-Co involve a close control of the process parameter such that only the cobalt phase melts without degrading the WC particles. Such degradation may occur in two ways:

- Oxidation of WC leading to the formation of $CoWO_4$ and WC_2 [32].
- Dissolution of WC in the cobalt matrix leading to a formation of brittle phase like CoW_3C which embrittles the coating [33].

An increase in the spraying distance and associated increase of in-flight time lead to a loss of carbon and a pickup of oxygen. As a result the hardness of the coating decreases. An increase on plasma gas flow rate reduces the dwell time and hence can control the oxidation to some extent. However, it increase the possibility of cobalt dissolution in the matrix [34].the other option to improve the quality of such coating is to conduct the spraying procedure in vacuum [33].

Often carbide like TIC, TAC and NBC are provided along with WC in the cermet to improve upon the oxidation resistance, hardness and hot strength. Similarly the binder phase is also modified by adding chromium and nickel with cobalt [30]. The wear mechanism of plasma sprayed WC-Co coating depends on a number of factors, e.g. , mechanical properties , cobalt content, experimental condition, mating surface etc. the wear mode can be abrasive, adhesive

or surface fatigue [35-39]. The coefficient of friction of WC-Co (in self-mated condition) increase with increasing cobalt content [38].A WC-Co coating when tested at a temperature of 450^{o}C exhibits signs of melting [40]. The wear resistance of these coating also depends on porosity [36]. These pores can act as source from where the cracks may grow. Thermal diffusivity of casting is another important factor. In narrow contact regions, an excessive heat generation may occur owing to rubbing. If the thermal diffusivity of the coating is low the heat cannot escape from a narrow region easily which a rise in temperature and thus failure occur owing to thermal stress [40]. The wear mechanism of WC-Co nano-composite coating on mild steel substrates has been studied in details [41]. The wear rates of such coatings are found to be much greater than that of commercial WC-Co composite coating. Presumably owing to an enhanced decomposition of nano-particles during spraying, wear has been found to occur by subsurface cracking along the preferred crack paths provided by the binder phase or failure at the inter-splat boundary.

Coating of tic or TiC+TaC with a nickel cladding are alternative solution for wear and corrosion problems. High temperature stability low coefficient of thermal expansion, high hardness and low specific gravity of these coating may outperform other materials, especially in steam environment [30]. Instead of nickel, nickel-chromium alloy can serve as the matrix material [42-43]. The mode of wear can be adhesive, abrasive, surface fatigue or micro-fracture depending on operating condition [39, 43].

A coating of Cr_3Cr_2 (with Ni-Cr alloy cladding) is known for its excellent sliding wear resistance and superior oxidation and erosion resistance , through its hardness is lower than that of WC [30]. After spraying in air, Cr_3Cr_2 losses carbon and transforms to Cr_7Cr_3. Such transformation generally improves hardness and erosion resistance of the coating [44]. The sliding wear behavior of the Cr_3Cr_2-Ni-Cr composite against various metals and ceramics has been studied by several authors [36, 39, 45]. It is felt that at lower loads the wear is owing to the detachment of splats from the surface. As the load increase melting, plastic deformation and shear failure come into play.

2.3.2 Oxide Coatings

Metallic coating and metal containing carbide coating sometime are not suitable in high temperature environments in both wear and corrosion applications. Often they fail owing to oxidation or decarburization. In such case the material of choice can be an oxide ceramic coating, e.g. Al_2O_3, Cr_2O_3, TiO_2, ZrO_2 or their combination. However, high wear resistance, chemical and thermal stability of these materials are counter-balanced by the disadvantages of low value of thermal expansion coefficient, thermal conductivity, mechanical strength, fracture toughness and somewhat weaker adhesion to substrate material. The thickness of these coating is also limited by the residual stress that grows with thickness. Therefore, to obtain a good quality coating it is essential to exercise proper choice of bond coat, spray parameter and reinforcing additives [30].

1. **Chromia (Cr_2O_3) Coatings:** These coating are applied when corrosion resistance is required on addition to abrasion resistance. It adheres well to the substrate and shows an exceptionally high hardness of $2300Hv_{0.5\ kg}$ [30]. Chromia coatings are also useful in ships and other diesel engines, water pumps and printing rolls [30]. A Cr_2O_3 – 40 wt.% TiO_2 coating provides a very high coefficient of friction (0.8), and hence can be used as a brake liner [30]. The wear mode of chromia coating has been investigated under various conditions. Depending on experimental condition, the wear mode can be abrasive, plastic deformation, micro-fracture or a conglomerate of all of these [38-40, 46-48]. This material has also been tested under lubricated condition, using inorganic salt solution (NaCl, $NaNO_3$, Na_3PO_4) as lubricates and also at high temperature. The wear rate of self-mated chromia is found to increase considerably at 450^oC and plastic deformation and surface fatigue are the predominant wear mechanisms [49]. Under lubricated condition, the coating exhibits tribo-chemical wear [50]. It has also been tested for erosion resistance [51].

2. **Zirconia (ZrO_2) Coatings**: Zirconia is widely used as a thermal barrier coating. However, it is endowed with the essential qualities of a wear resistance material, i.e., hardness, chemical inertness etc. and shows reasonably good wear behavior. In the case of a pressed zirconia mated with high chromium containing iron (martensitic, austenitic or pearlitic), it has been found that in course of rubbing the iron transfer on to the ceramic surface and the austenitic material adheres well to the ceramic as compared to their

martensitic or pearlitic counterparts [52]. The thick film improves the heat transfer from the contact area keeping the contact temperature reasonably low; thus the transformation of ZeO_2 is prevented. On the other hand with the pearlitic or martensitic iron the material transfer os limited. The contact temperature is high enough to bring about a phase transformation and related volume change in ZrO_2 causing a stress induced spalling . In a similar experiment the wear behavior of sintered, partially stabilized sircinia (PSZ) with 8 wt. % yttria against PSZ and steels has been tested al 200^oC. When metals are used as the mating surface, a transferred layer soon forms on the ceramics surface (coated or sintered) [49]. In ceramics-ceramics system, the contact wear is abrasive in nature. However, similar worn particles remain entrapped between the contact surfaces and induce a polishing wear too. In the load range of 10-40N, no transformation of ZrO_2occure [49, 53]. However similar tests conducted at 800^oC show a phase transformation from monoclinic ZrO_2 to tetragonal ZrO_2 [54]. The wear debris of ZrO_2 sometime gets compacted in repeated loading and gets attached to the worn surface forming a protective layer [55]. During rubbing, pre-existing or newly formed crack may grows rapidly and eventually inter-connect with each other, leading to a spallation of the coating [56]. The worn particle gets entrapped between the mating surfaces and abrades the coating. The wear performance of ZrO_2 – 12 mol. % CeO_2 and ZrO_2- 12 mol. % Al_2O_3 coating against bearing steel under various loads has been studied [57]. Introduction of alumina as a dopant has been found to improve the wear performance of the ceramics significantly. Hear plastic deformation is the main wear mode. The wear performance of zirconia at 400^oC and 600^oChas been reported in the literature [58]. At these temperatures the adhesive mode of wear plays the major role.

3. **Titania (TiO_2) Coating**: Titania coating is known for its high hardness, density and adhesion strength [36, 39]. It has been used to combat abrasive, erosive and fretting wear either in essentially pure form or in association with other compounds [59, 60]. The mechanism of wear of TiO_2 at 450c under both lubricated and dry contact condition has been studied in the past [39, 40]. It has been found to undergo a plastic smearing under lubricated contact, where as it fails owing to the surface fatigue in dry condition. TiO_2- stainless steel couples in various speed load condition have also been investigated in detail [61]. At a relatively low load, the failure is owing to the surface fatigue and adhesive wear, whereas at a

high load the failure is attributed to the abrasion and delamination associated with a back and forth movement [62]. At low speed the transferred layer of steel oxidized to form Fe_2O_3 and the wear progresses by the adhesion and surface fatigue. At a high speed, Fe_3O_4 forms instead of Fe_2O_3 [63]. The TiO_2 top layer also softens and melts owing to a steep rise in temperature, which helps in reducing the temperature subsequently [64]. The performance of the plasma sprayed pure TiO_2 has been compared with those of Al_2O_3 – 40wt% TiO_2 and pure Al_2O_3 under both dry and lubricated contact condition [65]. TiO_2 shows the best results. TiO_2 owing to its relatively high porosity can provide good anchorage to the transferred film and also can hold the lubricants effectively [66].

4. Alumina (Al_2O_3) Coatings: Alumina is obtained from a mineral called bauxite, which exists in nature as a number of hydrated phases, e.g. boehmite (γ-Al_2O_3, H_2O), hydragillate and diaspore ($\alpha Al_2O_3.3H_20$). It also exists in several other metastable forms like $\beta,\delta,\theta,\eta,\kappa$ and X [67]. αAl_2O_3 is known to be a stable phase and it is available in nature in the form of corundum. In addition, αAl_2O_3 can be extracted from the raw materials by fusing them.

The phase transformation during freezing of the plasma sprayed alumina droplets has been studied in details [68,69]. From the molten particles, γ-Al_2O_3 tends to nucleate, since liquid to γ transformation involve a low interfacial energy. The phase finally formed upon cooling depends on the particle diameter. For particle diameter less than 10 μm, the metastable form is retained (γ, δ, β or θ). Plasma spraying of alumina particle having a mean diameter of 9 μm results in the development of the gamma phase in the coating after cooling [70]. The α-form is found in the large diameter particles. In fact large is the diameter; greater is the fraction of α-Al_2O_3in the cooled solid. This form is desirable for its superior wear properties. Other than the cooling rate, one way to achieve the phase finally formed is to vary the temperature of the substrate. If the substrate temperature is kept at 900^0C, the δ phase forms. The α-Al_2O_3 can be formed by raising the temperature of the substrate to 1100^0C resulting a slow cooling. During freezing the latent heat of solidification is absorbed in the still molten pool. If this heat generation is balanced by the heat transfer to the substrate, columnar crystals grow. On the other hand, if the aforesaid heat transfer is faster than the heat injection rate from the growing solidification front, equi-axed crystals are supposed to form.

In reality columnar crystals are generally found. There are several advantages of alumina as a structural material e.g., availability, hardness, high melting point, resistance to wear and tear etc. it bonds well with the metallic substrates when applied as a coating in them. Some of the applications of alumina are in bearings, valve, pump seals, plunger, engine components, rocket nozzles, shields for guided missiles, vacuum tube envelops, integrated circuits etc. Recently plasma sprayed alumina-coated railroad component are being used in Japan [71].

Properties of alumina can be further complemented by the particulate (TiO_2, TiC) or whisker (SiC) reinforcement limits the gain growth, improves strength and hardness and also retards crack propagation through the alumina matrix [72]. The sliding wear behavior of both monolithic and SiC whisker reinforced alumina has been studied [73]. The whisker reinforced composite has been found to have good wear resistance. The monolithic alumina has a brittle response to sliding wear, whereas the worn surface of the composite reveals signs of plastic deformation along with fracture. The whisker also undergoes pullout or fracture.

TiO_2 is a commonly used additive in plasma sprayed alumina powder [74, 75]. It has a relatively low melting point and it effectively binds the alumina grains. However, success of an Al_2O_3-TiO_2 coating depends upon a judicious selection of the arc current, which can melt the powders effectively. This results a good coating adhesion along with high wear resistance. The wear performance of Al_2O_3 and Al_2O_3 – 50 wt% TiO_2 has been reported in the literature [65]. In dry sand abrasion testing, alumina outer formed other presumably owing to its high hardness [76]. In dry sliding at low velocity range, the tribo-couple (ceramic and hardened stainless steel) exhibits stick-slip [77]. At relatively high speed range, the coefficient of friction drop owing to the thermal softening of the interface [64]. The wear of alumina is found to increase appreciably beyond a critical speed and a critical load. Alumina has been found to fail by plastic deformation, shear and grain pullout. In dry and lubricated sliding as well, the mixed ceramic has been found to perform better than pure alumina. A coating of Al_2O_3- 50 wt% TiO_2 is quite porous and hence is quite capable of holding the transferred metallic layer which protects the surface [66]. Wear performance of such coating can further be improved by sealing of the pores by polymeric substances [78]. A low thermal diffusivity of the alumina coating results in a high localized thermal stress on the surface. However, the mode of wear of alumina is mainly abrasive. The pore size and

pore size distribution also play a vital role in determining the wear properties. The Al_2O_3-TiO_2 coating has a high thermal diffusivity and hence it is less prone to wear.

The sliding wear behavior of plasma sprayed alumina AISI-D_2 steel under different speed-load conditions has been reported [24]. Within the load range used (45N-133N), the wear vs. load plot shows a maxima. In the initial phase, the wear volume increase with the load for a given number of sliding cycles. Beyond a certain load, owing to both load and frictional heating, a major plastic flow occurs on the coating surface. The plastic flow leads to an increase in real area of contact and a corresponding reduction of normal stress, though the normal load increase [79]. As a result, wear decrease with decrease with an increase in load beyond a critical normal load. On the other hand, the wear vs. sliding speed plot also display a maxima within the speed range used (0.31 to 8 m/s), at a low speed range, the asperities move against each other and deform each other in the process. As the speed is increased, the asperities are subjected to heavy impacts and tend to get fracture from the root producing a higher volume of debris. At a very high velocity the friction temperature rise becomes high enough to soften the asperities and thereby to protect them from fracture. The wear rate keeps low under such circumstances. Therefore, the plastic deformation and brittle fracture form the failure mechanisms.

2.3.3 Metallic Coating

Metallic coating can be easily applied be flame spraying or welding techniques making the process very economical. Moreover plasma sprayble metallic consumables are also available in abundant quantity. Metallic wear resistance materials are classified into three categories:

- Cobalt based alloys
- Nickel based alloys
- Iron based alloys

The common alloying elements in a cobalt-based alloy are Cr. Mo, W and Si. The microstructure is constituted by dispersed carbides of M_7C_3 type in a cobalt rice FCC matrix. The carbides provide the necessary abrasion and corrosion resistance. Hardness at elevated

temperature is retained by the matrix [80-81]. Something a closed packed inter-metallic compound is formed in the matrix, which is known as the Laves phase. This phase is relatively soft but offers significant wear resistance [82]. The principal alloying element in Ni- based alloys are Si, B, C and Cr. The abrasion resistance can be attributed to the formation of extremely hard chromium borides. Besides carbides, Laves phase is also present in the matrix [80].

Iron based alloys are classified into pearlitic / austensitis / marensitic steel and high alloy irons. The principal alloying elements used are Mo, Ni, Cr and C. the softer materials, e.g., martensitic, on the other hand provide wear resistance. Such alloys do not possess much corrosion, oxidation or creep resistance [80, 83, 84]. Nickel aluminide is another example of coating material for wear purpose, the pre-alloyed Ni-Al powder, when sprayed, react exothermically to form nickel aluminide. This reaction improves the coating substrate adhesion. In addition to wear application, it is also used as bond coat for ceramics materials [86].

NiCoCrAlY is an example of plasma sprayble super alloy. It shows an excellent high temperature corrosion resistance and hence finds application in gas turbine blades. The compositional flexibility of such coating permits tailoring of such coating composition for both property improvement and coating-substrate compatibility. In addition, it serves as a bond coat for zirconia based thermal barrier coating [73, 170].

2.3.4. Diamond Coating

Thin diamond films for industrial application are commonly produced by chemical vapour deposition (CVD), plasma assisted CVD, ion beam deposition and laser ablation technique [87, 88]. Such coatings are used in electronic devices and ultra-wear resistance overlays. The limitation of the aforesaid method is their slow deposition rates. The DIA-JET process involving a DC-Ar/H_2 plasma with methane gas supplied at the plasma jet is capable of depositing diamond films at a high rate [89]. However, the process is extremely sensitive to the process parameters. Deposition of diamond film is also possible using an oxy-acetylene torch [90]. One significant limitation of a diamond coating is that it cannot be rubbed against ferrous materials, owing to a phase transformation leading to the formation of other carbon

allotropes [91]. Diamond films are tested for the sliding wear against abrasive papers, where wear progress by micro-fracturing of protruding diamond grits. The process continues till the surface becomes flat and thereafter wear progresses by an interfacial spalling. Therefore, the life of the coating is limiting by its thickness [92].

2.4 On solid particle erosion wear of materials

Solid particle erosion (SPE) is a typical erosive wear made where particles strike against surface and promote material loss. During flight a particle carries momentum and kinetic energy, which can be dissipated during impact, due to its interaction with a target surface. It is to be noted that solid particle erosion is different from the other form of erosion like liquid impact erosion, slurry erosion, cavitation erosion etc. Material removal due to solid particle erosion is a consequence of a series of essentially independent but similar impact event. Thus, the contact between the hard particles and the component surface is of a very short duration. From this point of view, erosion is completely different from the other closely related processes like sliding wear, abrasion, grinding and machining wherein the contact between the tool/abrasive and the work-piece/target is continuous.

In some case SPE is a useful phenomenon, as in sand-blasting and high-speed abrasive water jet cutting, shot peening of rotating component, cutting of hard and brittle material by abrasive jet and rock drilling [93-95], but it is a serious problem in many engineering system, including steam and jet turbines, pipeline and valves used in slurry transportation of matter and fluidized bed combustion system. Gas and steam turbine operate in environments where the ingestion of solid particles is inevitable. In industrial applications and power generation, such as coal-burning boiler, fluidized bed and gas turbine, solid particles are produced during the combustion of heavy oils, synthetic fuels, pulverized coal etc. and causes erosion [96-97] leading to the damage of compressor gas path component, such as stator vanes or motor clades, leading to gradual changes in their surface finish and geometry [98-99]. Similarly, a helicopter operating in a sandy or dusty field will generate a dust cloud that will be ingested by the compressor resulting in a progressive metal loss from both the leading and trailing edges of the airfoils [100]. Erosion is thus expected whenever

hard particles are entrained in a gas or particle can be accelerated and their directions of motion can be changed by the fluid.

Degradation of materials due to solid particle erosion, either at room temperature or at elevated temperature, is encountered in a large variety of engineering industries is illustrated in table 2.1.

Table-2.1 Solid Particle Erosion On Variety of Engineering Industry

Systems	Components
Chemical plant	Transport tubes carrying abrasive materials in an air stream[101-103]
Hydraulic mining machinery	Pumps and valves[104]
Propellant system	Rocket motors trail nozzle, gun barrel[105]
Combustion system	Burner nozzle, reheater, super heater and economizer tube banks[106,107]
Fluidized bed combustion	Boiler heat exchanger tubes in bed tubes banks and expander turbine[106,108-110]
Coal gasification	Turbine, lock hopper valves[106]
Coal liquefaction	Valve to throttle the flow of product steam[106]
Aircraft engine	Compressor and turbine blades[111]
Helicopter engine	Rotor and gas turbine blades[93]

In order to minimize damage caused by erosive wear, many authors propose the use of surface coatings, fluidized bed combustion boilers, turbines and engines are normally exposed environments and the erosion leads to many accidents [112-115]. The ceramic coatings are considered as powerful barriers against deterioration of machine parts exposed to particulate flow at high temperature [116]. Ceramics coatings have great potential for

many applications due to their good thermal protectiveness, high hardness and wear resistance among other. For example, the wear resistance coating are widely used in textile industry to improve the life time of different thread guiding element, guiding and distribution rollers, ridge thread brakes, distribution plates, driving and driven rollers, gullets, tension rollers and thread brake caps [117].

Applications of ceramics coating produced by different deposition methods are increasingly used to extend the service life of mechanical components. This is because the coating themselves have high hardness and chemical inertness and have excellent wear resistance, which makes it possible to protect the surface from erosive environments. Friction and wear are surface phenomena and are of high concern especially in industrial component resulting in huge economic losses and sometimes lead to catastrophic failure [118]. Hence, it is of utmost importance to minimize their ill effects. Use of coatings would enhance the wear resistance as well as anti-friction resistance of the materials. In addition, coating enable use of relatively cheaper materials for machine components.

Recently, cermet coating are used to further increase the erosion resistance trough increasing the toughness of the coating [119-124]. The erosion resistance of the coating is influenced not only by the impact angle, particle velocity and environment temperature, but also is strongly dependent on the coating process [125-128]. For the application of these materials to components, different techniques in the field of surface engineering can be considered. Some researchers made use of process such as thermal spraying, sputtering, physical vapour deposition, chemical vapour deposition, detonation spraying and electro-spark detonation to obtain protective coatings against erosive wear [129-131]. Out of all these surface modification techniques, however, the most widely reported one is thermal spraying.

2.5 On Dry Sand Abrasion Wear of materials

There are a number of different types of wear. Low stress or scratching abrasion is probably the most predominate in the mining industry.. Extremely heavy wear takes place in construction and mining machineries, where large amounts of rocks and soil are processed.

The skip car in blast furnaces are used to transfer and charge raw materials such as coke, iron ore, sinter and additives like limes stone dolomites into the furnace. This Skip Car has to withstand heavy wear caused by loading and unloading of those raw materials onto the Car body, which subjects it to impact-abrasion wear caused by impacts and scratching by the minerals. A quantitative method of measuring a material's resistance to this scratching type abrasion is the Dry Sand Rubber Wheel Test having ASTM G65 standard. This test characterizes materials in terms of weight loss under a controlled set of laboratory conditions. Correlation to actual field conditions may be influenced by other wear parameters such as the amount of impact, corrosion, galling, etc. Nevertheless, valuable insight into a materials field performance may be gained by examining the results of this test against a material's chemistry and microstructure. This then is the criteria in which are materials used in abrasive wear applications should be subjected.

Although a great deal of work has been done on abrasive wear behavior of coated steels on two body abrasion, limited work has been carried out on three body abrasive wear on coated steels. After reviewing the existing Literature available on wear resistant coating and coating material and their failure, efforts are put to understand the basic needs of the composite industry. The conclusions drawn from this study is that the surface treatment increases the wear resistance of the surface material, it also modify the frictional behavior at the surface.

Thus the priority of this work is to modify the surface of the skip car surface material by suitable method. In the present work it is planned to replace the existing mild steel plate of skip car by carbide coated over lay plate to increase its service life. After coating the plates will be subjected to various tests like solid particle erosion test and three body abrasion test. Their wear resistance properties will be studied. After getting successful results they will be put to field trial at Rourkela steel plant, Rourkela.

Chapter 3

Chromium Carbide Overlay Plate

3.1 Introduction

The present scientific, engineering and economic problem is the wear of mechanical parts equipment caused by decrease of working surfaces properties. The wear mechanisms are very complex, because of interlinked factors, which intensity of interaction depends on the conditions type of environment, in which the mechanical parts are used but also on the type and parameters of the work. Based on the analysis of parameters responsible for the wear of mechanical parts, about 50% (of the parts) works in abrasive wear, 15% - adhesive wear, 8% - erosion, 8% - fretting, 5% - wear is due to corrosion and about 14% is just a combination of abrasive, erosive and corrosive wear [132]. The variety of the types of wear leads towards the use of specialized welding materials in order to ensure the highest possible wear resistance of the surface layers, in working conditions. One of those typical material used in industries are wear resistant plates. The type of the wear resistant plate and its properties are the factors influencing on individual parts in the mechanical equipment durability. This makes contribution to get significant material and economical savings. Wear resistant plates are modern solution in regeneration of worn machines parts and also for producing new parts which connect high wear and erosion resistance with costs reduction. Main economic advantage of these plates is regeneration possibility of big worn machines surfaces and equipment when a construction mass is not the most important working parameter. In the wear resistant plate production, most common process solution is Overlay by welding deposition technique. By proper choice of structure and surface layer chemical composition it is possible to extend the effective life-time of wear resistant plates and the result the lifetime of mechanical equipment [133, 134,135]. Wear resistant plates can be cut on different shapes and formed by bending or rolling. Then they are fixed to the regenerated

parts by continuous or discontinuous fillet welds depending on load type for taken wear resistant plate. Necessity to obtain an uniform layer with a thickness of about 50-80 [%] of base material, impose that processes have to be mechanized [132, 136, 137]. During overlay processes stresses can be formed as a result of a volume of changes of cool down metal. Because of differences of expansion coefficients between the deposited and base metal, cracks mesh form which does not decrease properties of deposit. Widest practical application of wear resistant plates is in power, extractive, steel and cement industries. These plates are useful in intensive scratching and erosion wear conditions. Thanks to using them, we can get significant material and economy savings (resulted from costs reduction, decreasing stop times needed to change worn parts for a new one) [93,132-145].

3.2 Overlay by welding deposition technique

In Welding deposition technique, the coating material is deposited by melting it onto the substrate and then fusing the molten material to the substrate. The coating material is supplied in the form of paste, powder, rod or wire and is melted by the heat generated by gas flame, electric arc or plasma arc-welding gun. In this process, a portion of the substrate material gets melted and this fusion zone becomes diluted in the welded metal. This dilution can affect the composition and micro-structure and hence the wear resistance and also ensures the best mechanical properties as it maintains the metallurgical continuity across the fusion boundary.

In our present problem, Mild Steel is the Substrate and Chromium Carbide is the coating material. The coating material's form (paste, powder, rod or wire) is decided by the manufacturer.

3. 3 Chromium Carbide Compound

Chromium carbide is a ceramic compound that exists in several different chemical compositions: Cr_3C_2, Cr_7C_3 and $Cr_{23}C_6$. At standard conditions it exists as a gray solid. It is extremely hard and corrosion resistant. It is also a refractory compound, which means that it retains its strength at high temperatures as well. These properties make it useful as an additive to metal alloy. When chromium carbide crystals are integrated into the surface

of a metal it improves the wear resistance and corrosion resistance of the metal, and maintains these properties at elevated temperatures. The hardest and most commonly used composition for this purpose is Cr_3C_2.

3.4 What is Chromium carbide overlay plate?

Chromium carbide overlay plate consists of a mild steel plate onto which a highly abrasive resistant welded overlay is deposited using Open arc or submerged arc process. Plate sizes typically range from 10 mm to 38 mm in thickness; width varies from 120cm to 240 cm and lengths from 240cm to 600cm. The overlay deposit may be in one or two layers, measuring 6mm or 10mm thick. Bead width may vary according to the method of manufacture but typically measure about 38mm wide and are random check cracked. Check cracking occurs as a natural phenomenon during welding and is controlled by the chemical composition of the overlay or by cooling methods. Overlay deposit chemistry ranges from 15% to 30% Chromium, 3.0% to 4.5% Carbon, Manganese and Silicon may vary from 1% to 4% each. Molybdenum may exist up to 3%. Deposit hardness varies from 400 BHN to 600 BHN. The finished plates can be formed and fabricated. Holes can be cut with either plasma or electro discharge machining (EDM) techniques

Fig 3.1 Chromium Carbide overlay plate

3.5 Hardness, Chemistry & Wear

A material's hardness has long been erroneously used as criteria for wear resistance. This can be demonstrated by comparing the wear resistance of an alloy steel with a white iron, both having hardness values of 550 BHN, ASTM G65 wear test results consistently show a marked superiority in wear resistance of the white iron.

The reason for such a disparity in wear resistance despite the two materials having identical hardness values, lies in the hardness test itself. Popular hardness test devices such as Brinnel and Rockwell measure material's macro hardness. Each metallurgical component of the material has its own micro hardness which then contributes to the macro hardness. The Alloy Steel, has a predominately single metallurgical component (Martensite) and it's micro hardness is nearly identical to the macro hardness. The White Iron has a dual metallurgical structure, consisting of Chrome Carbide, with a very high micro hardness, embedded in Austenite, with a very low micro hardness. The resulting Brinnel macro hardness value (550 BHN) is really an average of the two micro hardness values. Hardness values only become relevant when comparisons are made within a family of steels and this can be misleading at times. It is best therefore to dismiss any relationship between hardness and wear resistance. Actual chemical composition and resulting metallurgical structures should be considered as criteria. The role of alloying elements and temperature are very critical in deciding the hardness behavior of the components. Typical hardness of different materials and relative wear rate of different steels are given in Table-3.1and 3.2

TABLE3.1 TYPICAL HARDNESS FOR COMMON MATERIAL

SLNO	MATERIAL	HARDNESS(BHN)
1	Mild Steel	120
2	Stainless Steel	250
3	Hardness tool steel	650-700
4	Hard Chromium Plate	1000
5	Tungsten Carbide Plate	1400
6	Titanium Carbide Plates	2400
7	Diamond	8000
8	Sand	1000

TABLE 3.2 EFFECT OF CARBIDE LAYERS ON WEAR PROPERTIES

Condition	Dilution(%)	C	Cr	Wt. loss
Open Arc Wire		5.0	30.0	
Open Arc 1st Layer	40%	3.0	18.0	1.25
Open Arc 2nd layer	40%	4.2	25.2	0.40
Submerged Arc 1st layer	10%	4.3	28.0	0.33
Sub Arc 2nd layer	10%	4.55	30.0	0.19
Mild Steel				2.51

3.6 Methods Of Manufacturing Of Coated Plates

Various methods of manufacture have evolved over the years since the introduction of chromium carbide overlay plate. Currently, all popular manufacturing methods are characterized as follows:

1. Arc Welding Process Used
    - Open Arc
    - Submerged Arc or Fusion Bond welding

2. Base Plate Configuration Used
    - Flat Plate or Table Design
    - Cylindrical Drum

The selection of any of these variables can have a profound affect upon the quality, consistency, integrity and wear properties of the plate. An examination of each variable is described below.

3.6.1 Arc Welding Process

Two basic welding processes are used in the manufacturing of overlay plate; Open Arc and Submerged Arc. Each has its features and limitations. The consumer should be aware of

the welding process used because of its direct correlation between welding process and wear resistance as will be shown . But before a serious evaluation can be made, there are a few items that need clarification;

- All arc welding deposits consist of a mixture of the wire composition and base metal composition. The amount of this mixing is expressed as a dilution percentage. In other words, a 35% dilution factor for a welding process means that the resulting weld deposit consists of 35% base metal and 65% wire.
- The arc welding deposits are discussed above are thoroughly mixed. There is no visual division of either the base metal component or the wire component. It is a complete and homogeneous mixture of wire and base metal.

3.6.1.1 Open Arc Welding

Open arc welding (fig. 3.2) is accomplished with a cored wire of the proper diameter. No gas or flux is added to the process. All the slag, flux, gas cover and alloys are included within the core of the tube. The wire is fabricated from a low carbon strip and the critical ingredients are added during fabrication. The wire is then packaged for shipment in 500 Lb. containers for consumption. Since this is the only welding consumable used in overlay plate manufacturing, inventories are relatively simple. Process control is also quite simple since only standard arc voltages, currents and wire feed rates requires attention. Deposits are relatively smooth, but are susceptible to roughness and poor tie-in between the weld beads. The most severe limitation of the open arc welding process is its inability to produce chemical compositions acceptable for maximum wear resistance in the first layer. This inadequacy can be traced back to a combination of wire fabrication and process variables. The fabricated tube consists of a hole that will accept only a certain amount of alloys. In this case, about 30% Chromium and 5% Carbon plus other key ingredients. This is compounded by the fact that the open arc process inherently produces about 40% dilution. This equates to a deposit chemical composition of about 18% Chromium and 3.0% Carbon. It has been demonstrated through ASTM G65 abrasion tests that a minimum of 20% Chromium and 4% Carbon is required for acceptable wear. Second layers are also subjected to the effects of

dilution but to a lesser extent. Under above criteria, second layer will consist of 25.2% Cr and 4.2% Carbon. This is sufficient for acceptable wear.

3.6.1.2 Sumerged arc Welding/ Fusion bond Welding

Submerged Arc Welding is accomplished through the use of a solid or cored wire and added flux. The arc melts both the wire and the flux and forms a weld bead and an easily removable slag covering. Dilution factors are typically 30/40%. Fusion Bond Welding is also a **submerged arc** process but with the addition of alloy powder. The addition of powder greatly reduces the dilution to about 10%. By over alloying with alloy powder the 10% dilution factor can be overcome. Thus it is possible to deposit a chemical composition of 30% Chromium and over 4.0% Carbon within the first layer. This composition is quite acceptable from a wear standpoint.

Additional features included in the Fusion Bond Welding process are; smooth deposits with extremely shallow peaks and valleys, process control, deposit consistency. The major limitation is the inventorying of three welding consumables; wire, flux and alloy powder. However, it is the flexibility of arc welding process and deposit chemistry control that far outweigh this shortcoming.

From the above data above, it becomes apparent that the Sub Arc deposits are superior in wear resistance to Open Arc deposits.

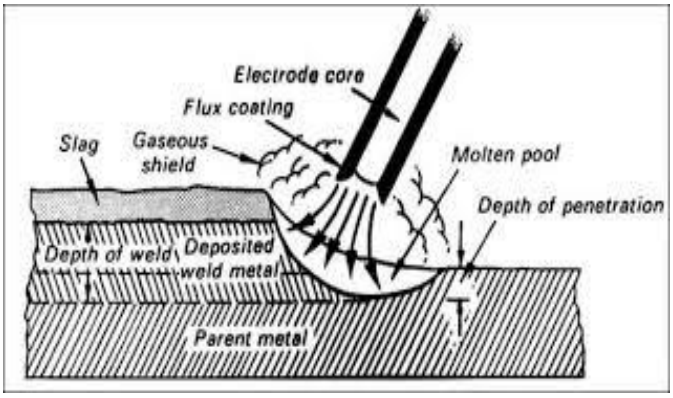


Figure 3.2 Open Arc Process

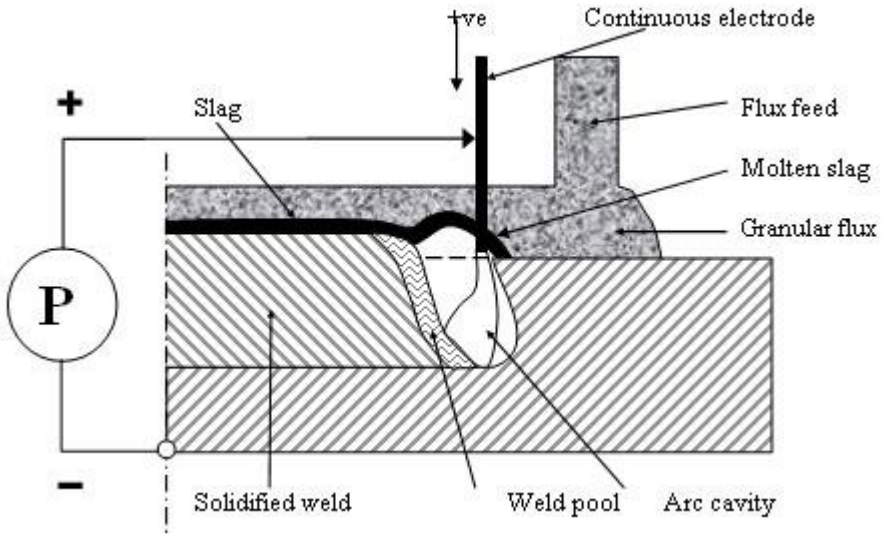


Figure 3.3 Submerged Arc Welding

3.6.2 Base Plate Configuration

Flat mild steel plate of required sizes were procured for overlay. The manufacturer has different options in configuration the plate for the overlay process but in present case the flat plate was placed on a specially designed flat table. This is known as Table Method which is described below.

3.6.2.1 Table Method

The obvious advantage with this configuration is the ease of plate handling. Since the plate is purchased as flat plate, it makes good sense to just place it on the table and overlay with either an open arc or Fusion Bond welding process. Once the overlay is complete, the plate is then subjected to a straightening or flattening process and then trimmed to size on a plasma cutting table. The process is quite simple and straight forward. However, serious complication often arises during the welding of base plates of less than ¾" thick. Distortions in the form of large humps, plague the process and compromise deposit integrity. Each time a hump is encountered by the welding arc, penetration and dilution of the base plate is increased. This means that the chemistry of the humped region could become unacceptable for maximum wear. The economics of the table approachable are quite attractive from a manufacturing standpoint.

Fig 3.4(a) chromium carbide overlay plate hard facing machine

Fig 3.4(b) Chromium carbide overlay plate flattening machine

3.7 Advantage of Chromium Carbide Overlay (CCO) Plate

- Can be cut, formed and welded
- Pipe fabricated 2″ ID and over
- Cost effective
- Stress relieved
- Extended service life
- Superior abrasion/impact resistant
- Good weldability to mild steel base
- Superior to ceramics
- Weld overlay can be applied to two sides for added strength and durability

3.8 Closure

Wear in materials is fundamentally technical and economic important . Wear is cause of huge losses. Variety of a wears processes leads to material specialization in aim of assurance as good as possible resistance on wear in specific conditions. Keeping this in mind, using chromium carbide plate in skip car becomes essential. To substantiate the wear resistance property of the coated plates, experiments have been carried out (Solid particle erosion test, Three body abrasion) in the laboratory conditions to assess the suitability of the material for actual operations in the steel plant.

Chapter 4

Abrasive wear behavior on chromium carbide overlay plate by dry sand wear test rig

4.1 Introduction

Abrasive wear is a common and critical problem in the industrial areas of agriculture, mining, mineral processing and earth moving whenever dirt, rock and minerals are handled by the machineries. Depending on the stress level during abrasive wear, it is often categorized as being low-stress or scratching abrasion, high-stress or grinding abrasion, gouging abrasion. Among them, low-stress abrasion occurs when lightly loaded abrasive particle impinges on and move across the wear surface, cutting and plowing material on microscopic scale. During this event, the abrasive remains relative intact during abrasion, in contrast to high-stress abrasion where the abrasive is crushed. A typical example of low-stress abrasion is the wear that occurs on a construction machine working with loose sand or dirt.

The abrasive wear resistance of a material has been related to a variety of material properties including composition, hardness, elastic modulus, yield strength and microstructure etc. Among them, material hardness has been considered the predominant factor. This can be explained by micro-cutting mechanism that contributes to material removal during abrasion. By increasing material hardness, the particle has less penetration depth; therefore, less material is scratched off by the abrasive particle. This has been expressed in simple terms through Archard's wear equation:

$$W_v = k_{ab} s F_N / H \qquad (4.1)$$

Where W_v is the volume loss due to wear, K_{ab} is the abrasive wear coefficient, S is the sliding distance of the abrasive under normal load F_N and H is the hardness of the material. Heat treated steel plates are widely used as abrasion resistance materials. The steel grades are usually classified based on their hardness level. Whenever higher abrasive resistance is needed, materials with extremely high hardness such as tungsten carbide(WC) and Chromium carbide (Cr_2C_3) are applied to create hard faces on steels to address some of the most severe abrasive wear environments.

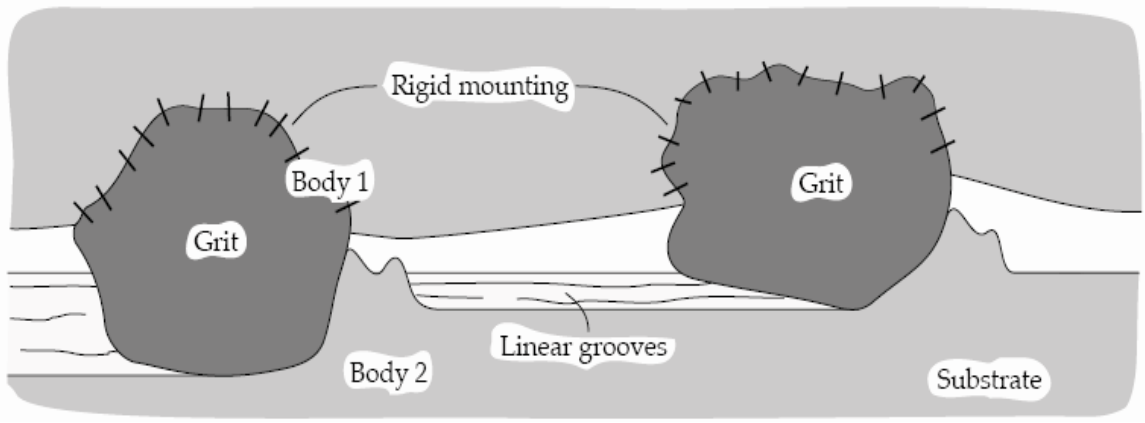
4.2Modes of Abrasive Wear

The way the grits pass over the worn surface determines the nature of abrasive wear. The literature denotes two basic modes of abrasive wear:

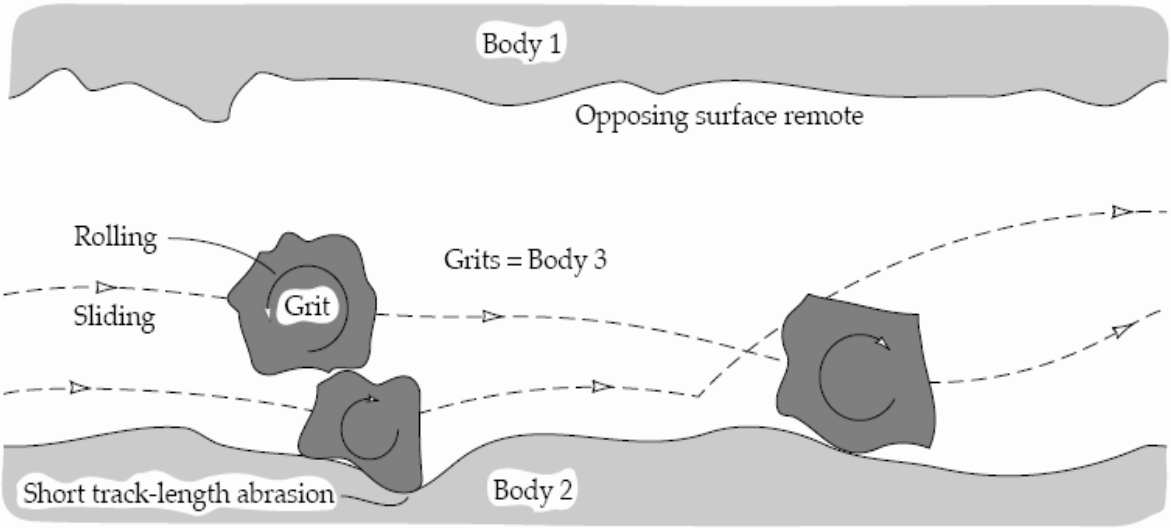
·(i) Two-body and

·(ii) Three-body abrasive wear.

Two-body abrasive wear is exemplified by the action of sand paper on a surface. Hard asperities or rigidly held grits pass over the surface like a cutting tool. In three-body abrasive wear the grits are free to roll as well as slide over the surface, since they are not held rigidly. The two and three-body modes of abrasive wear are illustrated schematically in Figure 4.1.



(a) Two-body mode



(b)Three-body mode

Fig4.1 Two and three-body modes of abrasive wear

Until recently these two modes of abrasive wear were thought to be very similar, however some significant differences between them have been revealed [146]. It was found that three-body abrasive wear is ten times slower than two-body wear since it has to compete with other mechanisms such as adhesive wear [147]. Properties such as hardness of the "backing wheel" which forces the grits on to a particular surface were found to be important for three- body but not for two-body abrasive wear. Two-body abrasive wear corresponds closely to the 'cutting tool' model of material removal

whereas three-body abrasive wear involves slower mechanisms of material removal, though very little is known about the mechanisms involved [148]. It appears that the worn material is not removed by a series of scratches as is the case with two-body abrasive wear. Instead, the worn surface displays a random topography suggesting gradual removal of surface layers by the successive contact of grits [149].

4.3 Experiment

4.3.1 Preparation of the test specimen

A mild steel plate of 8 mm thickness was cut to desired size to be placed suitable under the coating machine. After placing the plate at the required position under machine Chromium Carbide powders were fed through the hopper at the tip of wire electrode. The Carbide powder were allowed to deposited to the thickness of 4mm either in single layer or double layer on the base plate mild steel by fusion. The overlay plate was then taken out of the machine after giving three hours curing time. Specimens of dimension (25X25X12) mm were cut from the plate with the help of Plasma Arc Cutting machine for further experimentation.

The above samples were fabricated at M/s Wearresist Technologies Pvt. Ltd. Vadodara.

4.3.2 Dry sand rubber wheel testing machine

The three-body abrasion wear test was performed on a dry sand rubber/wheel abrasion tester designed as per ASTM G 65 test standard. The set-up of the testing machine and its schematic diagram are shown in Fig 4.2(a) and (b) respectively. The setup for the test is capable of creating a three-body abrasive wear environmental for analyzing the wear properties of the prepared composites. The apparatus consists of sample holder, nozzle, abrasive hopper, rubber wheel, particle collecting bag, steel disk, and an arrangement for the application of load. Dry angular silica sand of size (150-250)μm with sharp edges was used as abrasive for the present study. The abrasive particles of particular size were stored in abrasive hopper. The samples were cleaned with acetone in ultrasonic cleaner and then dried. The initial weight was measured using an electronic balance having a least count of (1×10^{-3}

)g. The samples were then mounted on the specimen holder and pressed against the chlorobutyl rubber wheel using a liver arm with a specified force while controlled flow of abrasive particles abraded the surface. The chlorobutyl rubber wheel used is of thickness 12.7 mm rimmed on a 228mm diameter wheel. The wheel was rotated at a speed ranging from 200 to 1000 rpm at an approximate sliding velocity of 0.83 to 4.16 m/s. Static force of 10 ,20, 30, 40 N were applied on the specimen using dead load on the load arm. The pivot axis of the lever arm lies in plane, tangential to the rubber wheel surface and normal to the horizontal diameter along which the load was applied and moisture free silica abrasive particles were passed between the specimen and the rubber wheel. The specimen holder was designed to ensure that wear scar location remains the same, even after removal and replacement of samples. The abrasive feeding system consists of a hopper that allows silica sand to fall under gravity through the nozzle onto a rubber wheel. The rubber wheel was rotated by a motor through timer belt and the speed of the motor determined the discharged rate of silica sand. The contacting surface of the rubber wheel was in the direction of the flow of sand. The experimental conditions are summarized in Table 4.1. All the tests were performed in a dry environment at laboratory room temperature. Each abrasion test lasted for 5 minutes. After completion of each test the specimen was removed from the holder, cleaned with acetone and weight loss measurements were recorded. This procedure was repeated until the abrasive wear rate attains a steady-state value. Wear volume were computed from the weight loss measurements. The same test procedure and conditions were maintained and new samples were taken for every set of applied load, sliding speeds and abrasive particle sizes.

Figure 4.3 shows the schematic representation of different zones on the wear scar under three-body abrasive wear test condition [150]. The wear scar has three different zones: an entrance zone where abrasive first comes in contact with specimen, central zone in which particle may roll as well as slide and an exit area where abrasive particles leave the specimen. The entrance and exit areas subjected to multiple indentations by angular abrasive particles, whereas in central zone the angular particles have a rolling component to their motion across the specimen surface and it creates repeated contact on the loading surface. These may lead to localized fatigue damage and removal of the materials surface.

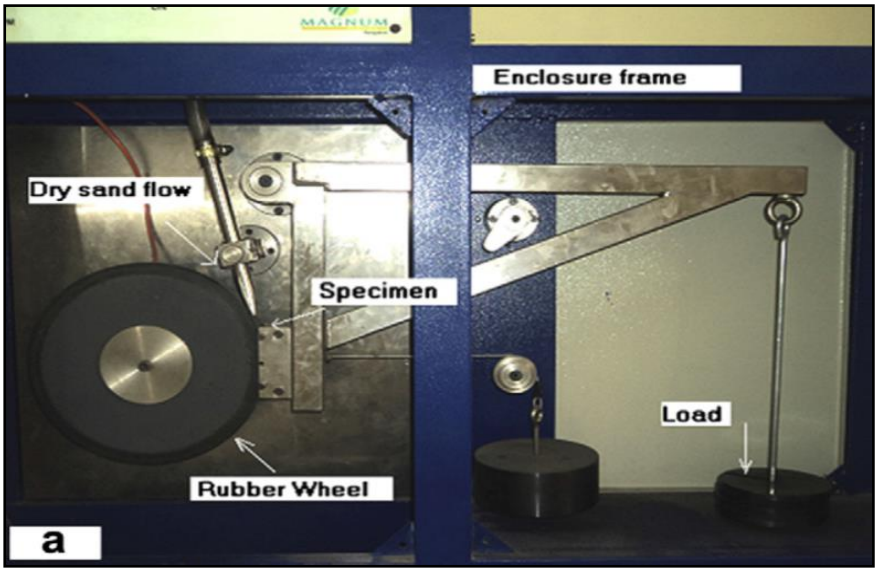


Fig 4.2(a) Test rig used for Dry sand Rubber wheel

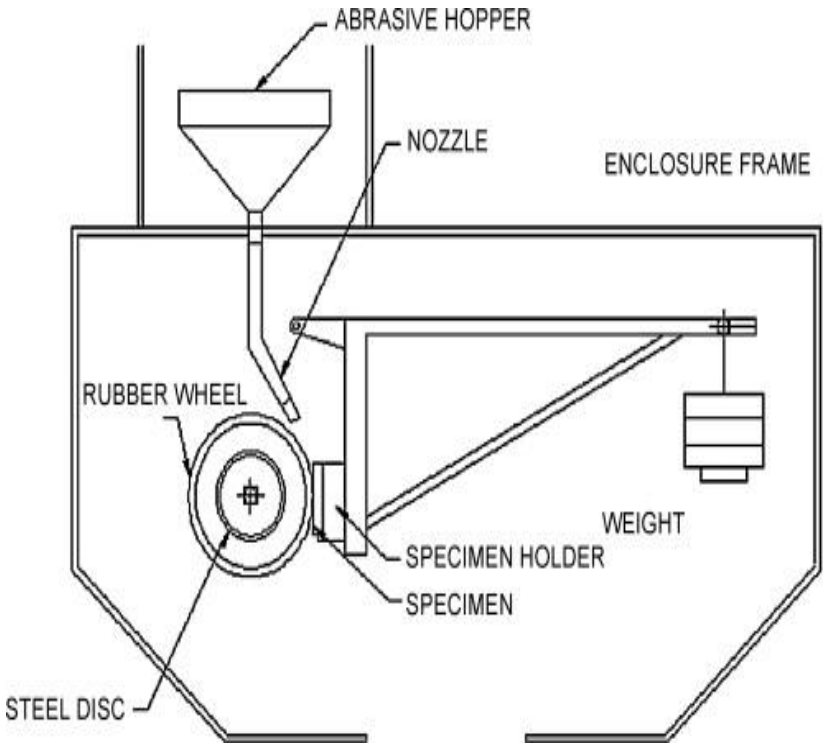


Fig 4.2b Schematic diagram of abrasive wear test rig

Table-4.1Experimental Parameters Dry sand Rubber wheel testing m/c

Load	10N,20N,30N,40N
Speed of Rubber Wheel	200 RPM(V=2.4 m/s)
Diameter of Rubber Wheel	228.6 mm
Abrasive particles	Silica Sand , angular
Abrasive Size	150-250 mm
Sand Flow Rate	200 g/min
Size of Specimen	75mm x 25 mm x 12 mm
Material of the Specimen	Mild Steel, Manganese Steel , Chrome Carbide overlay Plate

4.4 Measurement of Wear

Wear volume (ΔV) , Wear Rate (W_r) and specific wear rate (K_0) wear calculated from the following equations [150].

$$\Delta V = \frac{\Delta m}{\rho} \text{ mm}^3 \qquad (4.2)$$

$$W_r = \frac{\Delta V}{Ma} (\text{mm}^3/\text{gm}) \qquad (4.3)$$

$$K_0 = \frac{\Delta V}{LD}\left(\frac{mm3}{Nm}\right) \qquad (4.4)$$

Where Δm is the mass loss (g), ρ is the density of the test material (g/cc), Ma is the mass of the abrasive(g), $\Delta V(mm^3)$ is the volume loss, L is the applied load on the sample(N),D is the sliding distance (meter).

The actual load will be multiplied by 2.4 times as 2.4 is the leverage ratio of the Test rig. So the actual load for 10N, 20N, 30N, 40N will become 24.5N, 49N, 73.5N, 98N respectively.

The values of the mass loss, volume loss, wear rate and specific wear rate for different materials (Mild steel, Manganese steel, Chromium carbide coated sample) and mass loss, wear volume, wear rate of exclusive chromium carbide sample with respect to cumulative weight of abrasive as well as with respect to sliding distance were calculated using the above equations (4.2,4.3,4.4) and are listed in Table 4.2-4.4.

Fig.4.4 shows some worn out samples of dry sand rubber wheel machine. The wear marks are clearly visible on the photograph.

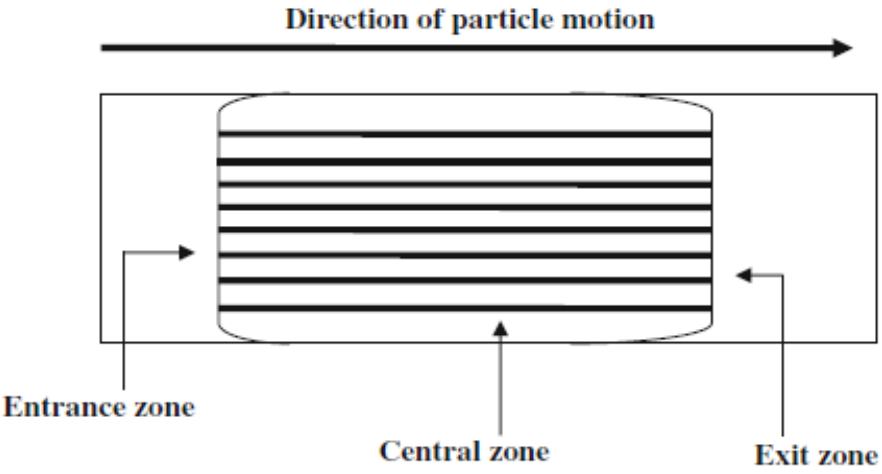


Fig. 4.3. Schematic representation of different zone on the wear scar

Fig 4.4 Wear mark on Dry sand wear test samples

Table 4.2 Weight loss, Wear volume, wear rate, Specific Wear rate of different Material with respect to varying Load

Material	Load(N)	Initial weight (g)	Final weight (g)	mass loss (g)	Wear Volume (cm^3)	Wear rate$\times10^{-6}$ (cm^3/g)	Ko $\times10^{-7}$ (cm^3/Nm)
Mild steel (ρ=7.85 g/cm^3)	24.5	173.68	173.63	0.05	0.006369	6.369	3.63
	49	173.010	172.942	0.068	0.008662	8.662	2.468
	73.5	170.660	170.581	0.079	0.010063	10.063	1.911
	98	167.660	167.540	0.12	0.015286	15.286	2.178
Manganese steel (ρ=7.88 g/cm^3)	24.5	195.146	195.116	0.03	0.003807	3.80711	2.1695
	49	194.393	194.353	0.04	0.005076	5.07614	1.4463
	73.5	191.753	191.703	0.05	0.006345	6.34518	1.2053
	98	188.382	188.302	0.08	0.010152	10.1523	1.4463
Chromium Carbide (ρ=6.68 g/cm^3)	24.5	219.265	219.245	0.02	0.002994	2.99401	1.7061
	49	218.419	218.388	0.031	0.00464	4.64072	1.3222
	73.5	215.453	215.412	0.0401	0.006003	6.00299	1.1403
	98	211.665	211.605	0.0606	0.009071	9.07186	1.2924

Table 4.3 Weight loss, wear volume, wear rate with respect to cumulative weight of abrasive at varying Load

Material - chromium carbide, density – 6.68 g/cm^3,flow rate of abrasive-200 g/min

Load (N)	initial weight(g)	final weight(g)	mass loss(g)	wear volume(cm^3)	Cumulative weight of abrasive(g)	wear rate×10^{-6} (cm^3/g)
24.5	221.4	221.38	0.02	0.002994	1000	2.99401
	221.38	221.348	0.032	0.00479	1500	3.19361
	221.348	221.309	0.039	0.005838	2000	2.91916
	221.309	221.268	0.041	0.006138	2500	2.45509
	221.268	221.22	0.048	0.007186	3000	2.39521
	221.22	221.17	0.05	0.007485	3500	2.13858
	221.17	221.112	0.058	0.008683	4000	2.17066
49	230.46	230.43	0.03	0.004491	1000	4.49102
	230.43	230.394	0.036	0.005389	1500	3.59281
	230.393	230.35	0.043	0.006437	2000	3.21856
	230.35	230.303	0.047	0.007036	2500	2.81437
	230.303	230.253	0.05	0.007485	3000	2.49501
	230.253	230.197	0.056	0.008383	3500	2.39521
	230.197	230.136	0.061	0.009132	4000	2.28293
73.5	225.15	225.11	0.04	0.005988	1000	5.9
	225.11	225.065	0.045	0.006737	1500	4.49
	225.065	225.015	0.05	0.007485	2000	3.74
	225.015	224.96	0.055	0.008234	2500	3.29
	224.96	224.9	0.06	0.008982	3000	2.99401
	224.9	224.83	0.07	0.010479	3500	2.99401
	224.83	224.76	0.07	0.0104	4000	2.61976
98	228.12	228.06	0.06	0.008982	1000	8.98204
	228.06	227.996	0.064	0.009581	1500	6.38723
	227.996	227.928	0.068	0.01018	2000	5.08982
	227.928	227.857	0.071	0.010629	2500	4.2515
	227.857	227.78	0.077	0.011527	3000	3.84232
	227.78	227.702	0.078	0.011677	3500	3.33618
	227.702	227.621	0.081	0.012126	4000	3.03144

Table 4.4 Weight loss, wear volume with respect to sliding distance at varying Load Material - chromium carbide, density – 6.68 g/cm^3, sliding distance per minute=143.25 meter

load (N)	Initial wt. (g)	Final wt. (g)	Wt. loss (g)	Wear volume (mm3)	Sliding distance(meter)
24.5	220.2	220.192	0.008	0.001198	286.5
	220.192	220.18	0.012	0.001796	573
	220.18	220.164	0.016	0.002395	859.5
	220.164	220.144	0.02	0.002994	1146
	220.144	220.12	0.024	0.003593	1432.5
49	221.4	221.388	0.012	0.001796	286.5
	221.388	221.37	0.018	0.002695	573
	221.37	221.346	0.024	0.003593	859.5
	221.346	221.314	0.032	0.00479	1146
	221.314	221.274	0.04	0.005988	1432.5
73.5	220.8	220.784	0.016	0.002395	286.5
	220.784	220.762	0.022	0.003293	573
	220.762	220.734	0.028	0.004192	859.5
	220.734	220.704	0.03	0.004491	1146
	220.144	220.12	0.024	0.003593	1432.5
98	222.2	222.178	0.022	0.003293	286.5
	222.178	222.149	0.029	0.004341	573
	222.149	222.113	0.036	0.005389	859.5
	222.113	222.07	0.043	0.006437	1146
	222.07	222.025	0.045	0.006737	1432.5

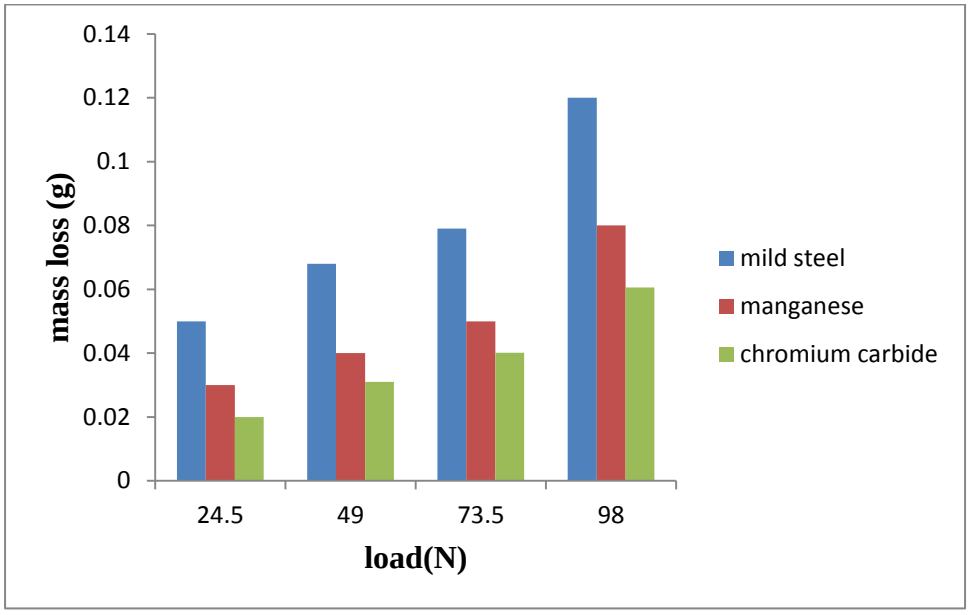


Fig 4.5 variation of mass loss with Load of different materials

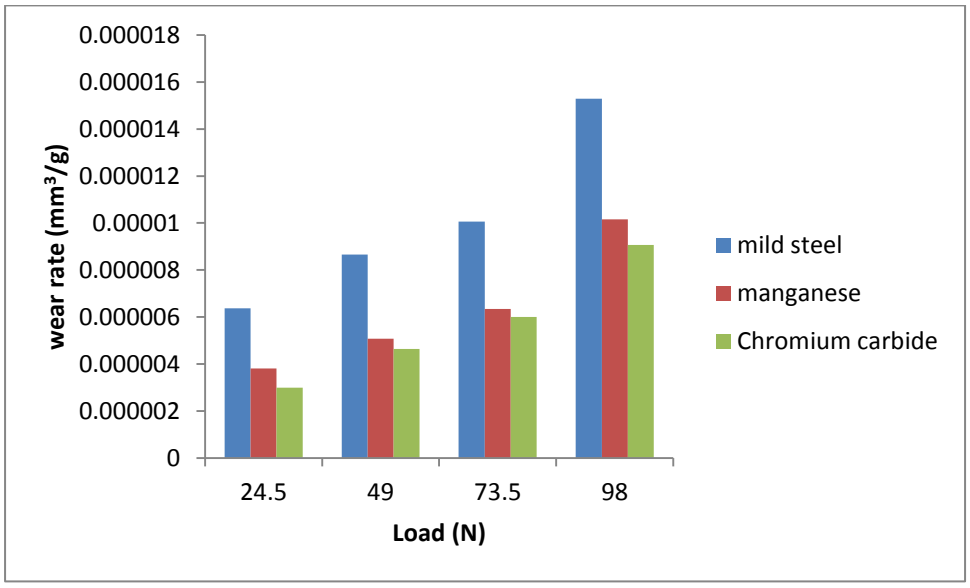


Fig. 4.6 Variation of wear rate with Load of different materials

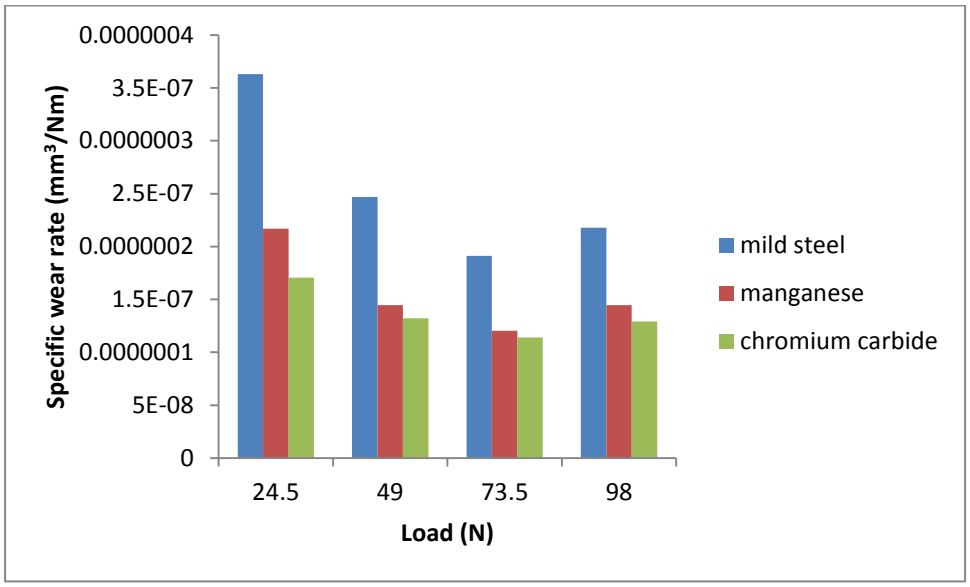


Fig. 4.7 variation of Specific wear rate with Load of different material

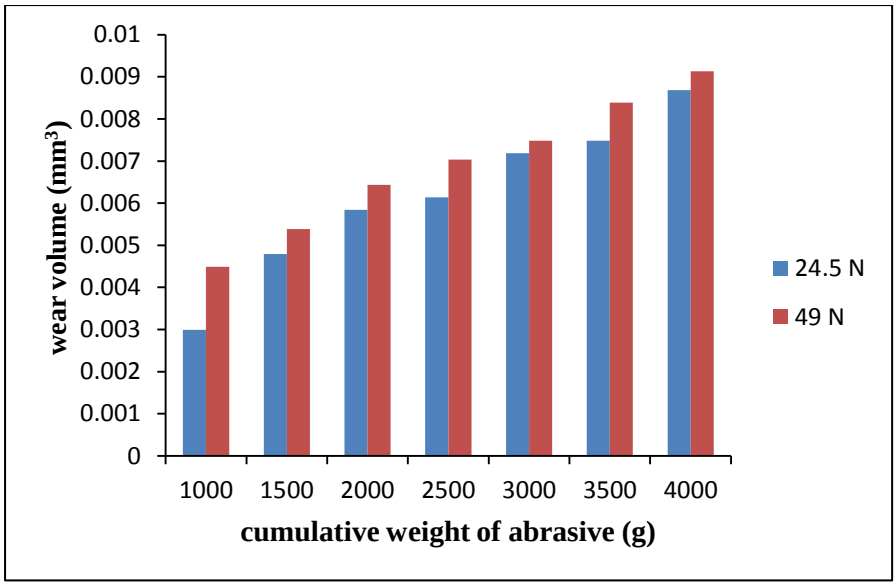


Fig. 4.8(a) variation of wear volume with cumulative wt. of abrasive for load 24.5N,49N

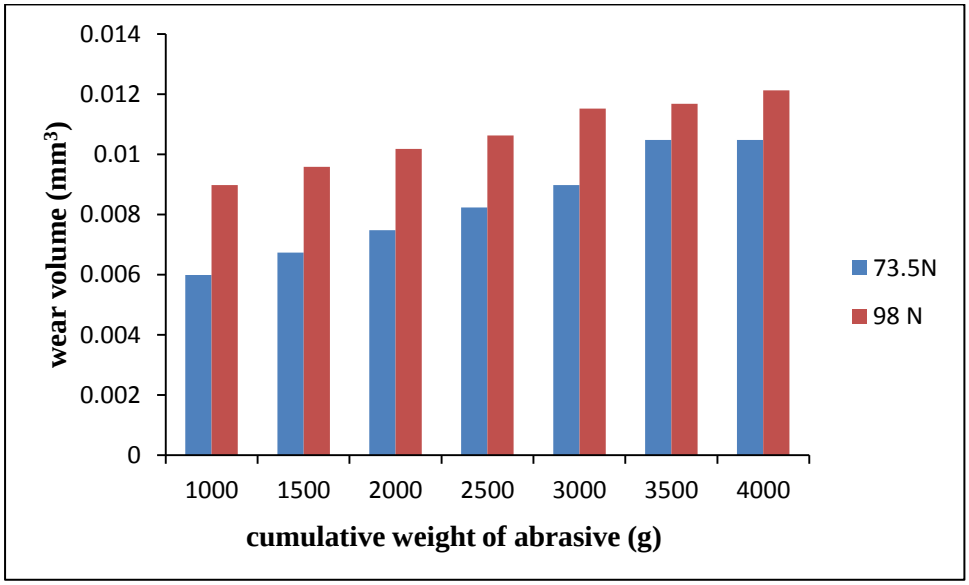


Fig. 4.8(b) variation of wear volume with cumulative wt of abrasive for load 73.5N,98N

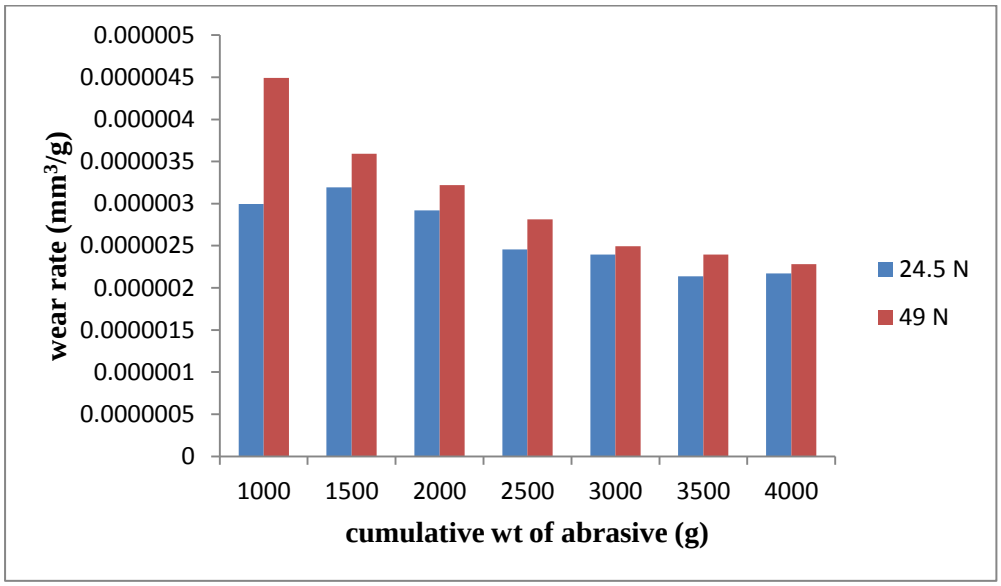


Fig. 4.9(a) variation of wear rate with cumulative wt of abrasive for load 24.5N,49N

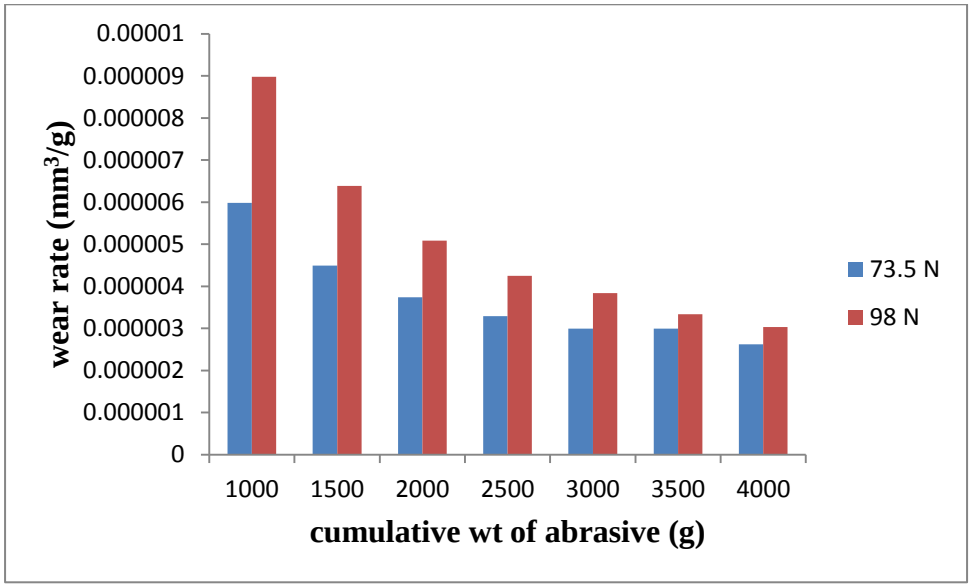


Figure 4.9(b) Variation of wear rate with cumulative wt of abrasive for load 73.5N,98N

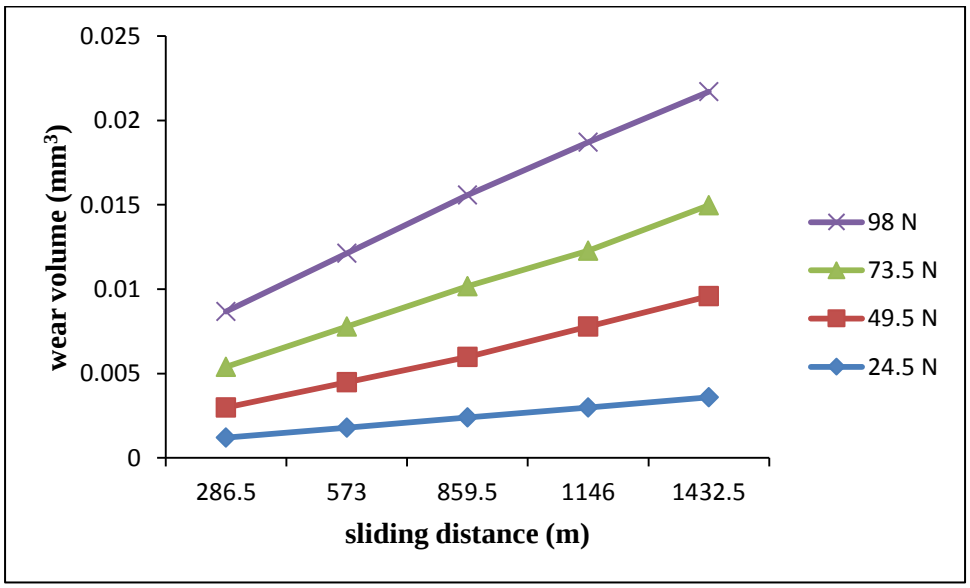


Figure 4.10 Variation of wear volume with Sliding distance for different Loads

4.5 Result and Discussion

Figure 4.5 shows the mass loss of different materials subjected to different load ranging from 24.5N to 98N. It is seen that as the load increases, mass loss also increases. The mass loss is minimum for 24.5N and maximum for 98N for all materials. This is because as the load increases the specimen is pressed more to the rubber wheel and more frictional loss occurs which is responsible for higher loss of material from the surface.

It is also seen from the above figure that mass loss of mild Steel > manganese Steel> chromium carbide coated steel. This is because of the hardness of the material. As the hardness increases, the mass loss becomes less under different Load.

Figure 4.6 shows the wear rate of different material with load ranging from 24.5-98N. It is clear from the figure that wear rate is lowest for chromium carbide coated steel.

For characterization of the abrasive wear behavior of the composite, specific wear rate is employed. This is defined as the volume loss of the composite per unit sliding distance and per unit applied load. Figure 4.7 shows decrease in specific wear rate up to 73.5N load, and thereafter it increases with increasing load. Chromium carbide is found to have lower specific wear rate as compared to other tested material (mild steel and manganese steel).

The rate of material removal depends prominently upon the quantity of the abrasives interacting with the material surface rather than exposure time. Figure 4.8(a) and 4.8(b) show wear volume as a function of mass of abrasive for the material subjected to abrasion test at different loads on Chromium carbide sample. The graph confirms the linearity of wear volume with the mass of the abrasive and shows strong dependence upon the applied load. Figure 4.8(b) shows that the steady state behavior of the materials is attained at around a sliding distance of 3000 m. Iwai et al. also discussed steady state wear rate after finite running-in.

The decrease in wear rate with increasing mass of abrasive is evident from figure 4.9(a) and found to be in the range 2.5E-5 to 4.5E-5mm3/g at low loads. At higher loads (Fig.4.9(b)), it was in the range of 4E-5 to 9E-5 mm3/g. During initial stage of abrasion, the hard abrasive comes in contact with the soft material and results in severe surface damage

and thus rate of material removal is very high. The wear rate of material tends to become steady with increasing exposure time.

The wear volume is also found to have linear relationship with sliding distance as shown in fig.4.10. It is found to be minimum at low loads and maintains an increasing trend with increase in Load.

4.6 Conclusion

- The wear rate increased with the increase in load, irrespective of the material which is found to be in conformity with the findings of other researchers. It is found to be minimum with chromium carbide over lay plate.
- The specific wear rate decreases up to a load of 30 N and there after it increases. This might have some relation with mechanical properties of the material which is to be found out.
- The rate of material removal depends prominently upon the quantity of the abrasives interacting with the material surface rather than exposure time.
- The wear volume is also found to have linear relationship with sliding distance.

Chapter 5

Solid particle erosion performance on chromium carbide overlay plate

5.1 Introduction

Tribology deals with relative motion of surfaces which comprises friction, wear of materials, scratching and rubbing. Further a sophistic definition portrays tribology as a science and technology of surfaces, in contact and relative motion, as well as support of activities that should diminishes the costs resulting from friction and wear [151-152]. Economic consequences of materials' wear are clearly described in the Rabinowicz book 4 – quoting a report to the British Government of 1966 when the word 'tribology' was used for the first time [153-154]. A significant part of tribology deals with the selection of materials and surface processing in as much as they affect wear [155].

Wear is a kind of loss of materials to a solid surface which occur due to relative motion of substance with respect to another substance. Formerly wear was defined as damaged to a surface. The most common form of that damage is loss or displacement of material and volume can be used as a measure of wear volume of material removed or volume of material displaced. For scientific purposes this is frequently the measure used to quantify wear. In many studies, particularly material investigations, mass loss is frequently the measure used instead of volume. This is carried out because of the relative ease of performing a weight loss measurement.

Wear causes a huge annual expenditure by industry and consumers. Most of this is replacing or repairing equipment that has worn to the extent that it no longer performs a useful function. In most of the agricultural industries 40% of the machine components replaced on equipment failed through wear. Estimates of direct cost of wear to industrialized nations vary from 1% to 4% of GNP and it is

estimated that 10% of all energy generated by man is dissipated in various friction processes. This direct cost includes replacements of wear part, an increase in the work load and time, loss of productivity, as well as loss of energy and the increased environmental liability.

In 1960s a systematic exertions in wear research had investigated in the industrial nations. Thus the magnitude of losses caused to mankind (which can be expressed in percentage points of GDP) makes it absolutely necessary to study ways to minimize it. Thus minimizing wear, affects the economics of production in a major way. Even though in the twenty-first century there are still wear problems present in industrial applications. This actually reveals the complexity of the wear phenomenon [155].

There are different types of wear such as abrasive, adhesive, fatigue and erosive wear, for metal matrix composite erosive wear is particularly interesting. In addition, composites acquire a significant place when it comes to operating in a dusty environment where resistance to erosion becomes an important aspect.

Solid particle erosion occurs whenever hard particles along with gas or liquid medium impinged on a surface at any significant velocity which results in progressive loss of material from a solid surface due to mechanical interaction between that surface and the erodent particles. The erosive wear is one of the most encountered types of wear and has recently been a subject of a number of researches [156-158]. The effect of particle erosion on structural and engineering components has been recognized for a long time [159]. Damage caused by erosion has been reported in several industries for a wide range of situations.

Degradation of materials due to solid particle erosion, either at room temperature or elevated temperature is encountered in a large variety of engineering industries. At the same time the erosion process has been used to advantage in a number of situations like sand blasting of castings, shot peening of rotating components, cutting of hard and brittle materials by abrasive jets and rock drilling. Thus the technological and commercial significance of erosion can not be overlooked.

5.2 Mechanism of Erosive Wear

Barkoula and Karger-Kocsis [160] presented in 2002 a review article on the solid particle erosion of polymers and polymeric composites focusing on the dominating mechanisms, the most discussed influencing parameters and the different trends observed in the literature. A detailed analysis was given on the effect of experimental conditions (erodent velocity, erodent characteristics, erodent flux rate) and target material characteristics (morphological-, thermal-, thermo mechanical-, and mechanical properties) on the erosive response of polymers and polymer matrix composites.

Erosive wear involves several wear mechanisms which are largely controlled by the various parameters such as particle material, the angle of impingement, the impact velocity, and the particle size. Figure-5.1 summarizes the most important ones. All have important effects on erosive wear; this effect tends to show variations depending upon whether the material tested are ductile, semi ductile or brittle.

According to Bitter [161], erosion is a material damage caused by the attack of particles entrained in a fluid system impacting the surface at high speed. Hutchings [162] defines it as an abrasive wear process in which the repeated impact of small particles entrained in a moving fluid against a surface result in the removal of material from the surface. Erosion due to the impact of solid particles can either be constructive (material removal desirable) or destructive (material removal undesirable), and therefore, it can be desirable to either minimize or maximize erosion, depending on the application. The constructive applications include sand blasting, high-speed water-jet cutting, blast stripping of paint from aircraft and automobiles, blasting to remove the adhesive flash from bonded parts, erosive drilling of hard materials. Whereas the solid particle erosion is destructive in industrial applications such as erosion of machine parts, surface degradation of steam turbine blades, erosion of pipelines carrying slurries and particle erosion in fluidized bed combustion systems. In most erosion processes, target material removal typically occurs as the result of a large number of impacts of irregular angular particles, usually carried in pressurized fluid streams.

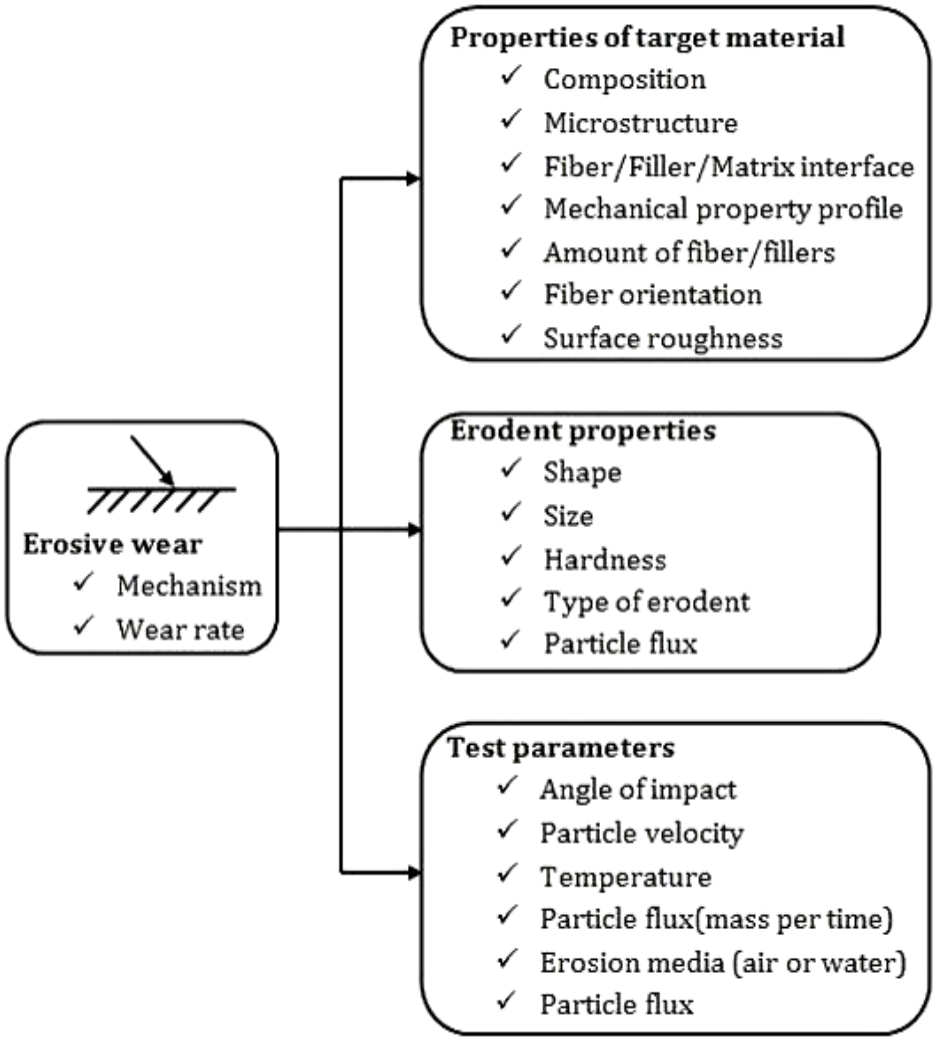


Figure-5.1 Influence of material, erodent and test parameters on erosive wear performance

It is generally recognized that erosive wear is a characteristic of a system and is influenced by many parameters. Laboratory scale investigation if designed properly allows careful control of the tribo-system whereby the effects of different variables on wear behavior of PMC scan be isolated and determined. The data generated through such investigation under controlled conditions may help in correct interpretation of the results. General factors influencing erosion test are given in Table-5.1. E is the mass removed divided by the mass of particles [163].

Table-5.1 General factors influencing erosion [163]

Eroded surface properties Hardness	Ductile: ***E*** is inversely proportional to the Vickers hardness Brittle: very little correlation
Stress level	Ductile: little effect on ***E*** Brittle: more effect on ***E***
Surface finish	Rougher surfaces raise ***E*** (this is a transient initial effect)
Eroding particle properties Size	Ductile: no effect for particle diameters ≥ 100 pm; lower ***E*** for particle diameters ≤ 100 /Jrn Brittle: ductile behavior for particle diameters ≥10 /μm
Shape	Angular particles produce more wear
Hardness	Harder particles produce more wear (they also tend to be more angular)
Flow and environmental conditions Angle of impingement	Ductile: maximum erosion at about 20° Brittle: maximum erosion at about 90°
Particle velocity	Ductile: $E \alpha U_0^{2-3}$ Brittle: $E \alpha U_0^{3-5}$
Particle flux (mass per time)	Generally small effect on ***E***
Temperature	Less effect than predicted from corresponding change in hardness (for temperatures less than half the melting point in Kelvins)

5.2.1 Influence of Impact angle (α) on Erosive wear rate

Among the various parameters, Impact angle is one of the most important parameters for the erosion behavior of composite materials. Dependence of erosion rate on the impact angle is largely determined by the nature of the target material and other operating conditions. The impact angle is

usually defined as the angle between the trajectory of the eroding particles and the sample surface. Impact can range from 0° to 90°.

At zero impact angle there is negligible wear because the eroding particles do not impact the surface, although even at relatively small impact angles of about 20°, severe wear may occur if the particles are hard and the surface is soft. If erosion rate goes through a maximum at intermediate impact angles, typically in the range 15°<α<30°, it is concluded that the '**ductile mode of erosive wear**' prevails. Ductile material erosion wear involves the removal of material by plastic deformation. Conversely if the maximum erosion rate occurs at high impact angles i.e. α=90°, then the behavior of the material is purely '**brittle mode**' is assumed. Brittle erosion involving the removal of material by fracture processes. It is generally seen that reinforced composites have been found to exhibit **semi-ductile behavior** with the maximum erosion rate at intermediate angles, i.e. 45°< α< 60°. The relationship between the wear rate and impact angle for ductile and brittle materials is shown in Figure-5.2.

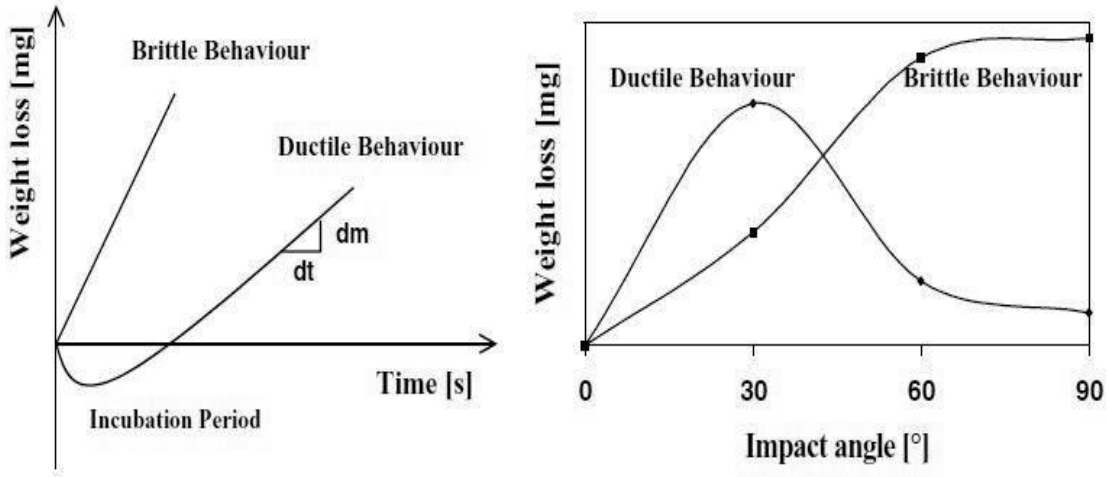


Fig.5.2 Schematic representation of the effect of impact angle on wear rates of ductile and brittle materials [160]

5.2.2 Influence of Impact velocity (υ) on Erosive wear rate

The velocity (υ) of the erosive particle has very strong effect on the wear process. If the velocity is very low then stresses at impact are insufficient for plastic deformation to occur and wear proceeds by surface fatigue [164]. When the velocity is increased it is possible for the eroded material to deform plastically. In this case, wear is caused by repetitive plastic deformation. At brittle wear response, wear proceeds by sub surface cracking. At very high particle velocities melting of the impacted surface may even occur.

From medium to high velocity, once steady state conditions have reached erosion rate (E_r) can be expressed as a simple power function of impact velocity (v) [164] equation:

$$E_r = k v^n \tag{5.1}$$

Where 'k' is an empirical constant of proportionality includes the effect of all the other variables. The value of 'n' and 'k' can be found by least-square fitting of the data points in plots which represent the erosion rate dependence on impact velocity by using the power law. The characteristics of the erodent and that of the target material determine the value of the exponent 'n'. It has been stated that 'n' varies in the range of 2–3 for polymeric materials behaving in a ductile manner, while for polymer composites behaving in brittle fashion the value of 'n' is in the range of 3–5 [163].

In the case of metallic materials, a detailed analysis of a large amount of experimental data by Hutchings [165] has shown that under oblique impact conditions, the mean velocity exponent ('n') is 2.4. A similar analysis of the experimental data by Sundararajan and Shewmon [166] indicated a mean value of 2.55 for 'n' for erosion under normal impact. The above values of 'n' are in contrast with the values of around 3 reported for ceramics and values in excess of 5 observed in polymer matrix composites [167].

The velocity exponent is also influenced by other parameters such as impact angle, particle size etc. Goodwin et el [168] noted a decrease in the velocity exponent with decreasing particle size. The velocity exponent has also been observed to be a function of erodent particle shape [169,170].

5.3 Experiment

5.3.1 Preparation of the test specimen

The specimens of size (25mm×25mm×12) were prepared as per the procedure explained in chapter 4 art 4.3.1.

5.3.2 Measurement of impact velocity of erodent: double disc method

The most commonly used method for measuring impact velocity of the erodent particle is the double disc method. This method has been developed by Ives and Ruff [171]. It consists of a pair of metal disc mounted on a common shaft and the stream of erodent particle is arranged to strike the upper disc, which has a thin radial slit cut in it. The exit particles from nozzle impinge on the upper disc with some of the particles passing through the slit, which eventually erode a mark on lower disc. Two erosion exposures are made, one with the stationary disc and the other with the rotating disc at a known rpm. These exposures give rise to erosion marks A and B on the lower disc as shown in fig.5.3. Measurement of the angular displacement between these marks gives a measure of the flight time of the particles as they cross between the discs. The particle velocity (V) can be found by using the following equation.

$$V = \frac{L}{t} = \frac{Lv360^\circ}{\emptyset} \qquad (5.2)$$

Where L is the separation of two discs, t is time in second,$v$is rotation speed of disc per second and Ø is angular displacement between the marks. The above equation can also be expressed as

$$V = \frac{2\pi r v L}{S} \qquad (5.3)$$

Where "r" is radius from the disc center and "s" is linear separation of two marks. The details of impact velocity calibration at various pressures are given in table 5.2.

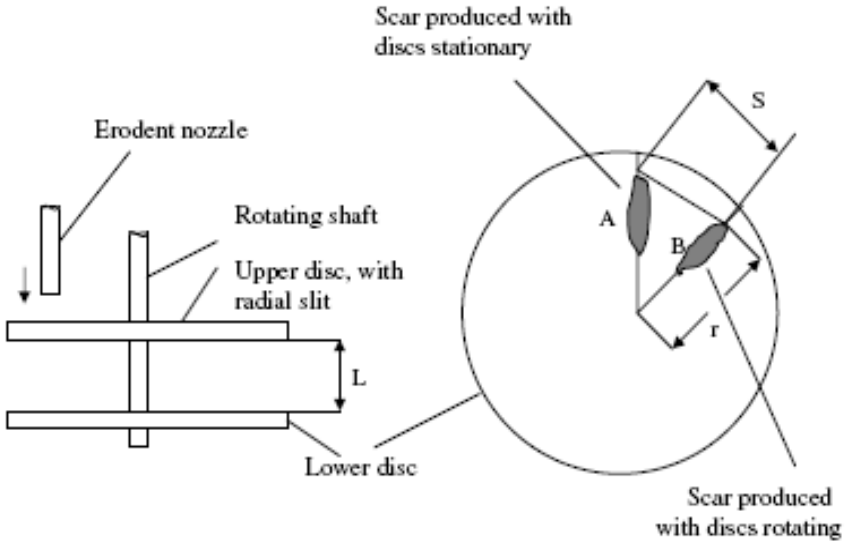


Fig. 5.3 Schematic diagram of methodology used for velocity calibration

Table-5.2 Impact velocity calibration at various pressures.

Pressure (bar)	**Speed of rotating disc(rpm)**	**Angle θ (°)**	**Velocity (m/s)**	**Avg. impact velocity(m/s)**
1 bar	2000	7.0	42.85	47.25
		6.5	46.15	
		6.0	50.00	
		6.0	50.00	
2 bar	2000	4.0	75.00	69.16
		4.5	66.67	
		4.0	75.00	
		5.0	60.00	
3 bar	2000	4.5	66.67	81.845
		4.0	75.00	
		3.5	85.71	
		3.0	100.00	

5.4 Test Apparatus & Experiment

The schematic Figure of the erosion test apparatus used for the present investigation designed as per ASTM-G76 standard is shown in Figure-5.4(a, b). The rig consists of an air compressor, a particle feeder, and an air particle mixing and accelerating chamber. The compressed dry air is mixed with the erodent particles, which are fed at a constant rate from a conveyor belt-type feeder in to the mixing chamber and then accelerated by passing the mixture through a tungsten carbide converging nozzle of 4 mm diameter. These accelerated particles impact the specimen, and the specimen could be held at various angles with respect to the impacting particles using an adjustable sample holder. The test apparatus has also been fitted with a rotating double disc to measure the velocity of the erodent particle. The impact velocities of the erodent particles has been evaluated experimentally using this rotating double disc method as mentioned in art 5.3.2.

5.4.1 Experimental Set Up

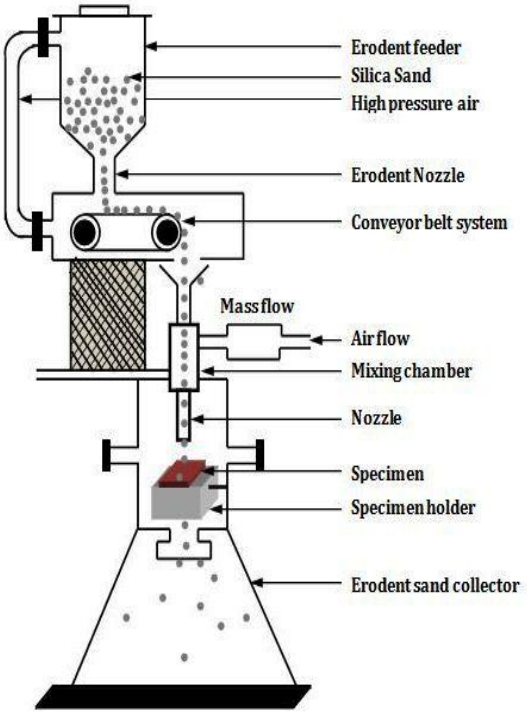


Fig. 5.4(a) Schematic diagram of erosion test rig

Fig.5.4 (b) Test set up

1. Sand hopper
2. Conveyor belt system for sand flow
3. Pressure transducer
4. Particle air mixing chamber
5. Nozzle
6. X-Y and Θ axis assembly
7. Sample holder

The conditions under which the erosion test has been carried out are given in Table 5.3. A standard test procedure is employed for each erosion test. Wear was measured by mass loss method. The samples were cleaned with a fine brush to remove any sand particles attached to the surface and then wiped with a fine brush to remove any sand particles attached to the surface and then wiped with a cotton plug dipped in acetone to avoid any entrapment of wear debris, prior and after each test then they were, dried and weighed to an accuracy of 1×10^{-3}g using an electronic balance prior to and after each test. The test samples after loading in the test rig were eroded for 20 min. at a given impingement angle and then weighed again to determine weight loss (Δw). The erosion rate $E_r$is then calculated by using the following equation:

$$E_r = \frac{\Delta w}{We} \qquad (5.4)$$

Where Δw is the mass loss of test sample in grams and W_e is the mass of eroding particle in grams (i.e. Testing time × particle feed rate). This procedure has been repeated until the erosion rate attains a constant steady-state value.

5.5 Erosion Efficiency

The surface hardness of material cannot give sufficient correlation with erosion rate because it determines the volume displaced by each impact and not really the volume of material eroded. Thus a parameter which will reflect the efficiency with which the volume that is displaced is removed should be combined with hardness to obtain a better correlation. The erosion efficiency is one such parameter.

G. Sundararajan et al. [172] proposed a term erosion efficiency 'η' to identify the brittle and ductile erosion response of various materials. It is identified as the fraction of the volume that is actually removed as erosion debris out of that which is displaced.

The erosion efficiency (ŋ) for the process was obtained by using the equation:

$$\Pi = \frac{2\,ErH}{\rho\times V2} \qquad (5.5)$$

where 'E_r' is the erosion rate (g/g), 'H' is hardness of eroding material (P_a) and 'V' is velocity of impact (m/s), 'ρ' is the density of the eroding material(kg/m^3).

But considering impact of erodent at any angle α to the surface, the actual erosion efficiency can be obtained by modifying Eq. (5.6) [173-174]

$$\eta = \frac{2ErH}{\rho V^2 sin^2\alpha} \qquad (5.6)$$

Where E_r is erosion rate (g/g), H is hardness of eroded material (Pa) and *v* is the impact velocity (m/s). 'ρ' is the density of the eroding material (kg/m^3).

The magnitude of 'η' can be used to characterize the nature and mechanism of erosion. For example, ideal micro-ploughing involving just the displacement of the material from the crater without any fracture (and hence no erosion) has zero efficiency (η= 0). In contrast, if the material removal is by ideal micro-cutting, 'η' is unity (η=1.0 or 100 %). If erosion occurs by lip or platelet formation and their fracture by repeated impact, as is usually the case in ductile materials, the magnitude of η will be low, i.e. $\eta \leq 100\%$. In the case of brittle materials, erosion occurs usually by spall and removal of large chunks of materials resulting from the interlinking of lateral or radial cracks and thus η can be expected to be greater than 100 %.

Experimental results of the erosion test for different Chromium Carbide Sample with various impingement angle and velocities are tabulated and presented in Table 5.4. Parameters characterizing the velocity dependence of erosion rate (E_r) are presented in Table 5.5.

Wear mark on few solid particle erosion test specimen are shown in fig 5.5.

Table-5.3 Experimental condition for the erosion test

Erodent	Silica Sand
Erodent Size (µm)	200±50
Impingement angle(α)	30,45,60,90
Impact velocity(m/s)	48,70,82
Erodent feed rate (g/min)	15
Test temperature	Room Temperature
Nozzle to sample distance (mm)	10
Nozzle diameter	4
Time (mins)	20

Fig5.5 Wear mark on solid particle erosion test samples

Table 5.4 Weight loss, erosion rate, erosion efficiency of Chromium Carbide overlay plate with respect to impact angle for a period of 1200 seconds.

Flow rate of Erodent = 25 g/min, Nozzle to sample distance = 10 mm,

Hardness of Chromium carbide (H_v) =760 N/mm^2, density (ρ) = 6.68 gm/cm^3

Impact velocity (m/sec)	**Impact angle**	**Weight loss(g)**	**Erosion rate (E_r) (g/g)**	**Erosion efficiency %(η)**
48	30	0.038	0.000076	9.4
	45	0.039	0.000078	9.7
	60	0.042	0.000084	10.45
	90	0.05	0.0001	12.44
70	30	0.105	0.00021	12.28
	45	0.108	0.000216	12.63
	60	0.117	0.000234	13.68
	90	0.118	0.000236	13.8
82	30	0.144	0.000288	12.27
	45	0.165	0.00033	14.06
	60	0.17	0.00034	14.49
	90	0.174	0.000348	14.83

Table 5.5 Parameters characterizing the velocity dependence of erosion rate

Material	**Impact angle**	**K**	**n**	**R^2**
Chromium carbide	30	8E-05	1.24	0.97
	45	8E-05	1.33	0.99
	60	9E-05	1.3	0.987
	90	10E-05	1.14	0.99

5.6 Result and Discussion

5.6.1 Effect of Impact Angle (α) on Erosion Rate of chromium carbide

Impact angle is defined as the angle between target material and the trajectory of the erodent. Dependence of erosion rate on the impact angle is largely determined by the nature of target material. As shown in figure 5.6, the maximum erosion rate is obtained at normal impact angle i.e. 90^0. It is also clear from the plot that erosion rate increases with increase in impact angle. Maximum erosion occurs in the range $60^0 – 90^0$. In between $30^0 – 60^0$, erosion rate increases linearly with respect to impact angle at higher velocity (82 m/s) while it is almost uniform at lower velocity of 48 & 70 m/s . From the above results based on earlier art5.2.1 [160], it is concluded that chromium carbide exhibit purely brittle behavior.

5.6.2 Effect of Impact velocity (v) on Erosion Rate of chromium carbide

The variation of steady-state erosion rate of chromium carbide samples with impact velocity at different impact angles are shown in Fig. 5.7(a). It can be observed from this graph that erosion rate of the sample increases with increase in the impact velocity.

The erosion rate is minimum at low velocity (48 m/s), gradually increases with increase in impact velocity. At impact velocity of 82 m/s, it attains maximum. This might have happened due to creation of severe plastic deformation on the composite surface at higher velocities.

As mentioned earlier (art 5.2.2) influence of impact velocity (v) on Erosive wear rate is one of the most important parameter for classifying the erosion behavior of any material. The least-square fits to data point were obtained by using power law in Fig. 5.7(b) and the values of ‘n’ and ‘k’ are summarized in Table – 5.5. The velocity exponents found for Chromium Carbide sample are in the range of 1.14-1.33. Though mean velocity exponent would have been in the range of 2.4 - 2.55 for metallic metals as was described by Hutchings [165] and Sundararajan and Shewmon [166] , the decrease in value of velocity exponent (‘n’) in this case may be because of lower in erodent particle size and shape as was explained by Goodwin [168].

5.6.3 Erosion efficiency chromium carbide

As discussed earlier (art 5.5), erosion efficiency is also one of the important parameter for classifying the erosion behavior of any material. The erosion efficiency was calculated by using equation (5.5). The calculated results are presented in Table-5.4 along with the weight loss and erosion rate. The erosion efficiencies is found to be in the range of 9.4%-14.83% indicating ductile behavior as concluded by G. Sundararajan et al. [172]. Variation of erosion efficiency with different impact velocity of erodent on chromium carbide overlay plate is shown in figure 5.8.

5.7 CONCLUSIONS

Experiments were conducted to study the solid particle erosion of Chromium Carbide Plates with silica sand as erodent. Based on the studies, the following conclusions are drawn.

- Study of influence of impingement angle on erosion rate of the composites reveals their brittle nature with respect to erosive wear. The peak erosion rate is found to be occurring at 60^0 - 90° impingement angle and at higher impact velocities.
- The erosion rate for all of the composites increases with increase of impact velocity. It is observed that the erosion rate followed the power law behavior with respect to impact velocity, $Er = kV^n$, and the value of the velocity exponent n is obtained in the range of 1.14 to 1.33.
- The erosion efficiency of the composite is found to be in the range of 9.4%-14.83% for different impact angle and different impact velocities studied. Basing on the result of erosion efficiency in the above range, it can be said based on the conclusion by G.Sundararajan et al. [172] that material is ductile in nature. However, the experiment results with impact angle and mass loss indicates brittle behavior of the composite. This is a typical situation occurring in the present case which needs further investigation.

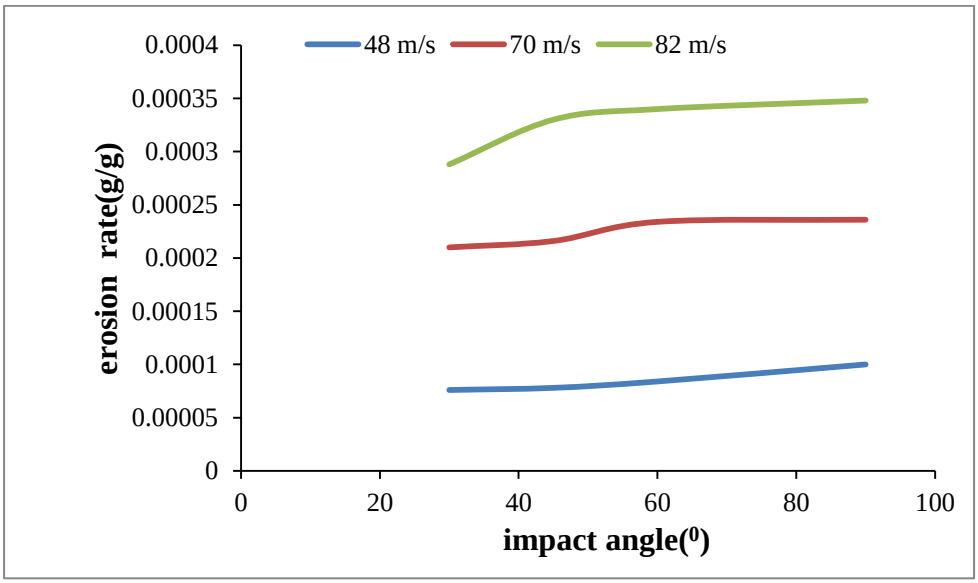


Fig.5.6 Variation of erosion rate with different impact angle on chromium carbide overlay plate

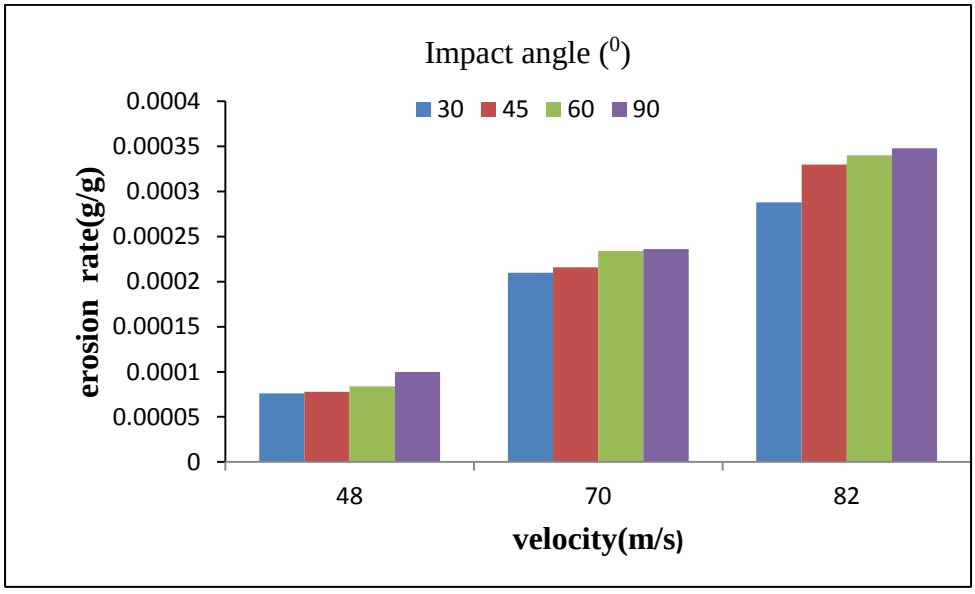


Fig.5.7 (a) variation of erosion rate with different impact velocity of erodent on chromium carbide overlay plate

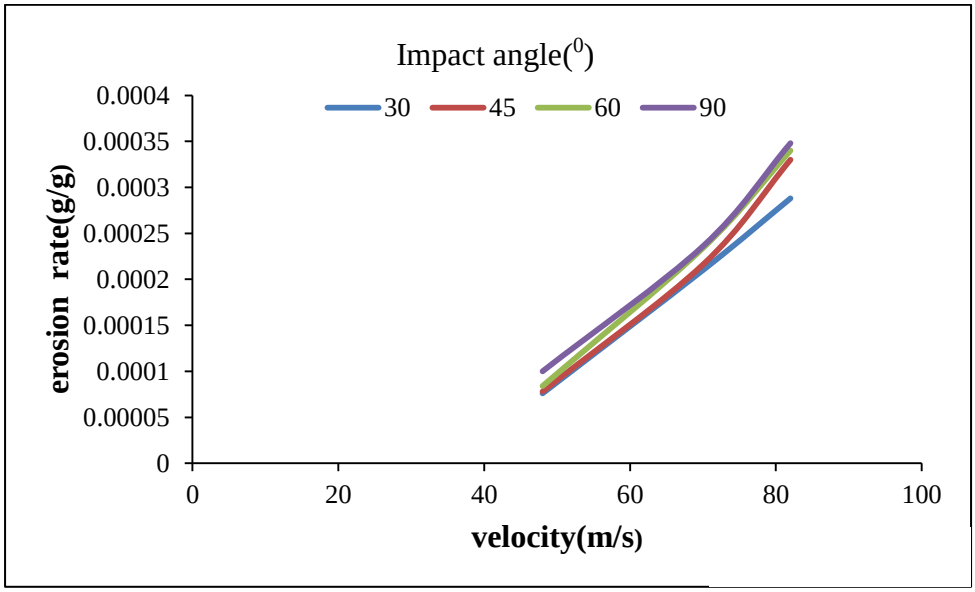


Fig.5.7(b) Variation of erosion rate with different impact velocity of erodent on chromium carbide overlay Plate

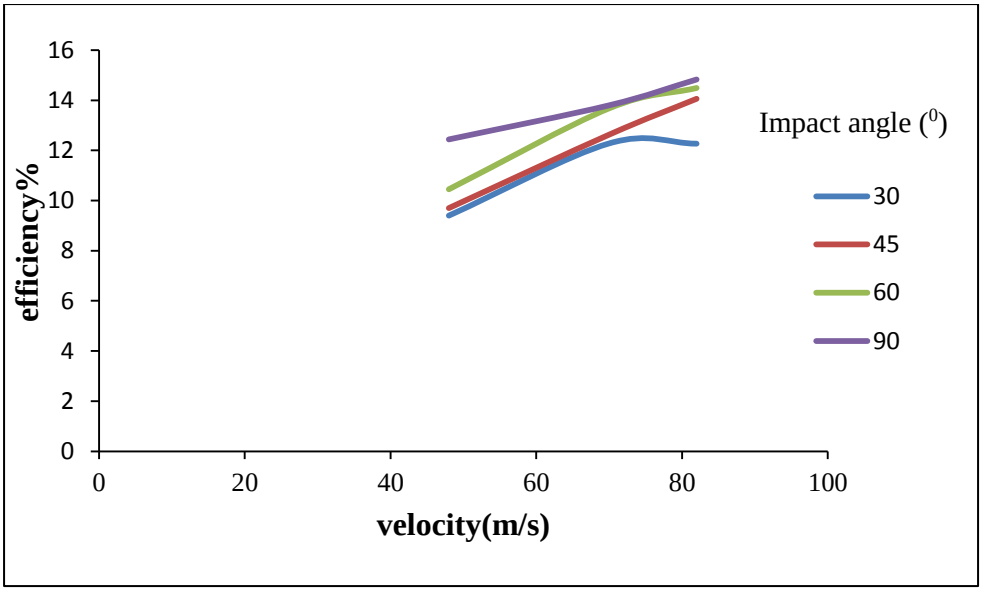


Fig.5.8 Variation of erosion efficiency with different impact velocity of erodent on chromium carbide overlay Plate

Chapter 6

Field Trial

6.1 Objective

With the objective of developing a new grade of wear resistance steel for use as Skip Car Liner Plates in Blast furnaces, this project was undertaken. The steel with new composition (chromium carbide) has shown better performance under Laboratory condition. Therefore the Plant trials were carried out at the blast furnace sites. The results were promising.

6.2 Commissioning

With due consultation with the Design Department and Management , Rourkela Steel Plant , it is suggested to carry out **Plant trial** in at least one of the Skip Car in Blast Furnace #3 .A suitable drawing was generated for the set of Chromium carbide plates from the existing drawing of the Skip Car. After going through the legal purchase procedure, Order is placed on M/s Wear Resist Technology, Vadodara. The party fabricated the Plates in its own premises and supply RSP in scheduled time .The plates (Fig 6.1) brought to Blast furnace Repair Shop and assembled in an old Skip car after removing its damaged liner plate completely. The proper fitment of the new set of Chromium Carbide liner plates in the Skip is ensured. Once the Skip is ready with the new liner plates in all respect, it was replaced on a scheduled shutdown day.

Fig. 6.1 Chromium Carbide Liner Plates (500mm×1070mm×16mm)

(16mm thickness plate consist of 10 mm mild steel as base plate and 6 mm is thickness of chromium carbide coating)

6.3 Observations of Wear Behavior of Skip Liner Plate

The chromium carbide plates were used as liner plates in one of the Skip Car in furnace-3. Normally the damages of skip liner plate are due to repeating falling of the particles as well as sleeting. First the materials fall on bottom liner plate and then load spreads over the entire space of skip car. Wear of plates mainly occur due to indentation on the surface.

On visual inspection after four months of commissioning it is found that there was no such damages to the coating has occurred. There is a minor scar in one or two places in the impact zone. This may be because of the raw materials are hitting those portion directly taking on the impact load where as rest of the portion of the plates comes under sliding contact with lesser wear.

More generation of Data on wear pattern of Chromium Carbide wear plates could be possible only after taking out of those plates from the skip car. Since these plates are now in good shape as appearing physically, it was let to run for some more days.

Service Life of Chromium Carbide plate have already exceeded our conventional liner plates i.e. mild steel or manganese steel. It has been six months since commissioning of those Chromium Carbide plates, no such stoppage of production has occurred on account of Skip Car while same was happening earlier in every three months. It is also expected that the Car can run three to four more months, even more with the existing plates.

6.4 Financial savings from the project

Basis of calculation:

- Cost of production/Ton of Hot Metal = Rs.17,540.00
- NSR of hot metal in terms of pig for 1 ton = Rs.24,700.00
- Profit Margin = Rate of Hot metal/Ton – Cost of Production = Rs.7,160.00

Table6.1 Financial Savings Analysis

Factors	**Savings**
Savings on account of hot metal Production (Assuming Skip Replacement time is 08 hrs. and 03 such breakdown were happening earlier per Annum)	3×8 hrs. ×200T of hot metal×Rs7160 per tonne =Rs.3.43 crores
Disturbance in Burden Movement	Intangible
Replacement Cost	1 lakh ×3 = Rs.3.0 Lakh
Man Hour savings for stopping 03 breakdown Per annum(Approx. 15 persons working in each b/down with Avg. wage of Rs 1000)	03*15* Rs1000 = Rs.45,000
Total	Rs.3.46,45,000/
Cost of one set Chromium Carbide plate	(minus) (-) 2,00,000/

Net Savings per annum (approx.) = Rs.3.44 Crores

It is worthwhile to mention that above financial analysis is done on one skip car and on one single furnace. If the above project will be implemented in other skip car as well as to other furnaces (RSP has four Blast furnaces with Skip car charging facility), the savings sum will be multiplied.

6.5 Recommendation

From laboratory investigation as well as plant trial it is concluded that Chromium Carbide Coated Plates are a suitable wear resistant.

- The Chromium Carbide (CrC) steel plates should be re-exposed for generating more data so that service life of CrC coat can be established.
- The CrC supply vendor base has to be developed for healthy competition.
- The CrC plates are be taken out from the skip car after 12 months and dimension are to be measured for further investigation.
- This project will also be helpful for other steel industry that produces hot metal through skip route.

Chapter 7

Miscellaneous

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PUBLICATION

No Publication has been made as the topic " Improvement in service life of Skip Car using chromium carbide overlay plate with special reference to Rourkela Steel Plant" is internal modification in Rourkrla Steel plant and hence in order to maintain confidientiality , it is let to be remain unpublished outside.

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